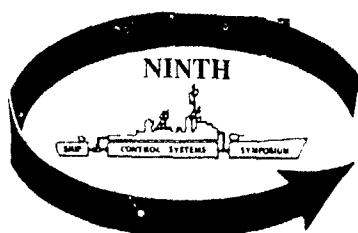


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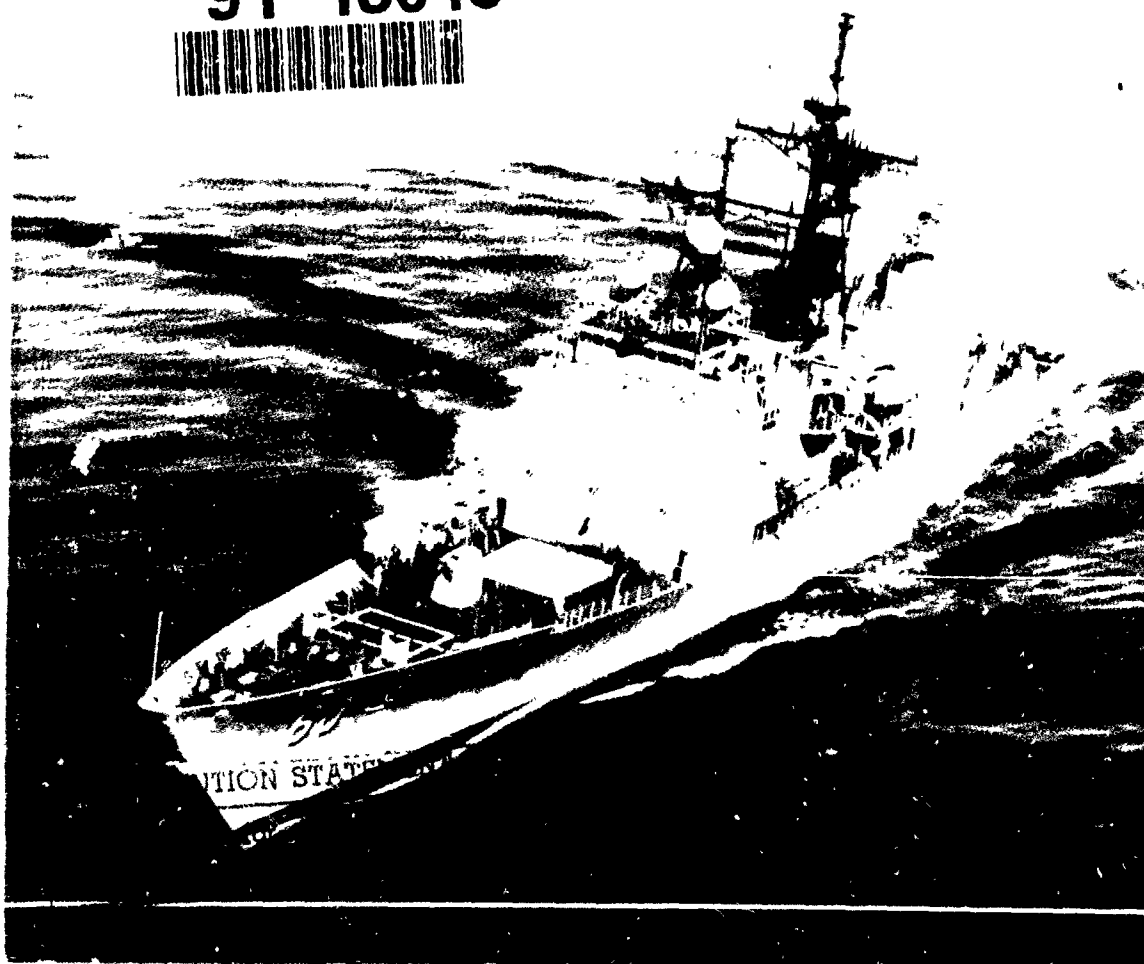
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SYMPOSIUM**

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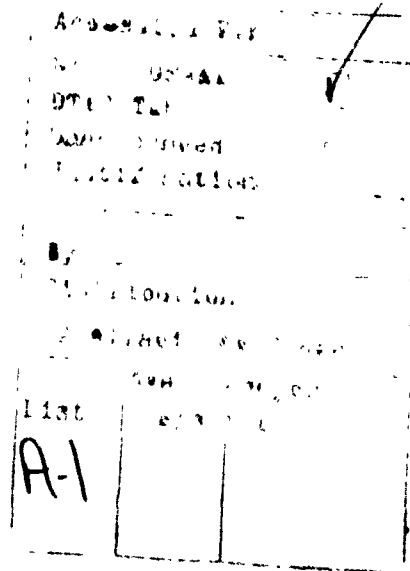
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## RESEARCH ON THE DEVELOPMENT OF AN EXPERT SYSTEM FOR NAVIGATION AT SEA

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Hayama IMAZU and Akio M. SUGISAKI  
Tokyo University of Mercantile Marine

### 1 ABSTRACT

It is an important solution to construct of expert system for navigation at sea in order to stem the deterioration of ship operational function due to the decrease of number of ship's crew.

Authors have constructed three prototype expert systems which are to be used for sub-systems of the expert system for navigation at sea. These three expert sub-systems are as follows:

- (1) for collision avoidance,
- (2) for coping with collision accident,
- (3) for engine operation at central control station in a ship.

They consist of a knowledge base, an inference engine, a working memory and a man-machine interface. The expertise is acquired from captain, officers, engineers and literature, which is represented in the form of a modified production rule. The number of adopted rules are more than 500. These expert sub-systems are written in PROLOG, and run on a mini-computer.

A set of evaluation criteria is proposed in order to evaluate the expert system which is under developing. The evaluation result is discussed mainly based on a questionnaire, an interview with watch officers and inference time measurement.

### 2. INTRODUCTION

Recently, the equipment automation and machineries have been introduced into navigation and communication systems. In quick ship operational innovation, rationalization as the number reduction of crews and automation of ship operation have been in progress to reduce crew size. In Japan, the operation of ship with only 11 crews is gravely recognized.

The equipment automation and machineries on a vessel could not supply the reduced navigation function, which relates to captain's, officers' and engineers' skill.

An expert system for navigation at sea is expected to be useful in the following ways:

- (1) To supply the reduced ship operators' expertise function,
- (2) To support ship operators,
- (3) To accumulate ship operators' know-how.

An expert system for navigation at sea is considered to be organized from

a lot of sub-systems which are shown in Fig.1.

The authors have developed three sub-systems among them. They are an expert system for collision avoidance, an expert system for coping with collision accident and an expert system for engine operation at the central control station in a ship.

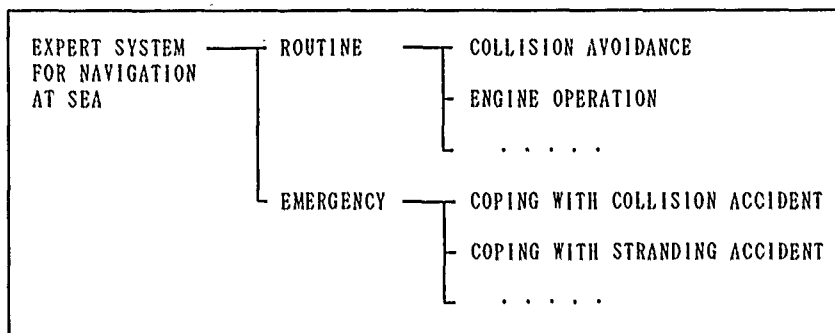


Fig.1 The Organization of Expert System

### 3. PROBLEM DOMAIN

The navigation expert system consists of a number of expert sub-systems which correspond to extensive experts activities in real marine environment. The authors have especially chosen the problem of collision avoidance, coping with collision accident and engine operation among many problems in this area, because of three reasons which are shown below.

- (1) A collision is the problem of basic and capital importance to a navigation system at sea.
- (2) In most of MO ships (a ship in which machinery space there is 0 person), watch officers operate the engine at central control station, which is the navigation bridge combined with the engine control room and the radio office. It is difficult to operate the engine as skillfull as engineers, however watch officers are educated how to operate the engine.
- (3) There is usually a little available time to resolve a navigational decision-making problem optimally or even successfully, in such situation a kind of technical issues arised. In this severe situation the captain or operators can not have enough available information to make optimal decision and to take appropriate action. And they can not have enough time to make their decision.

### 4. SUMMARY OF THE SYSTEM

The Expert system consists of a knowledge base, a working memory, an inference engine and user interface. The system organization is shown in Fig.2. The system is written in PROLOG on a mini-computer.

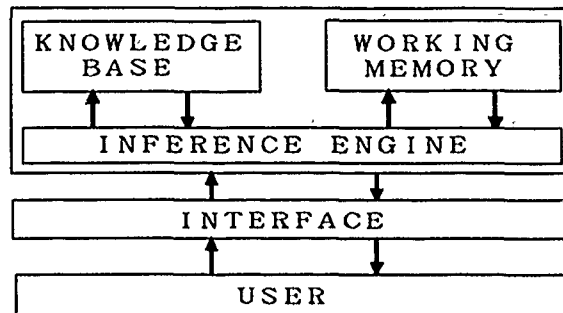


Fig.2 System Organization

#### 4.1 Knowledge representation

In the knowledge representation, a modified production rule model is proposed. A modified production rule is defined to be made up six parts. They are rule number part, "if" part, explanation part, "then" part, "for" part and "data\_set" part.

The explanation part and the "for" part are established for explanations. The "for" part shows the reason of inference to user and the explanation part shows the meaning of each rule.

The "data\_set" part is memorized in the working memory and this part performs the searching of the relevant rules which will be discussed in the next step. Therefore, the purpose of the "then" part is only to show the conclusion of inference to users.

```

rule(eo, eo, 1, 257)::EMERGENCY-RUN実行の検討
  if
    入出港 である and
    増速中 and
    危険回転数の通過の可能性あり and
    今後十分な行き脚確保が可能 でない
  then
    EMERGENCY-RUN検討
  for
    十分な速度による危険回転数通過が不可能
  data_set
    EMERGENCY-RUN検討.
  
```

Fig.3 An Example of Modified Production Rule in Japanese

When comparing with if-then form production rule structure, the modified production rule structure is a little more complicated. However, the modified production rule model has advantage of readability of rule, clarity of rule correlation, and so on. These advantages are necessary for system development, practical use and system management. An example of the modified production rule is shown in Fig.3. The rules are written in Japanese considering readability.

#### 4.2 Knowledge base

The knowledge based upon the technical and operational expertises has been acquired from captains, engineers, watch officers and some literature. It is important and essential to extract knowledge from experts to construct an expert system. The knowledge of the system is classified into two kind of knowledge, one is concerning judgement such as alteration ship course, increasing / decreasing of ship speed, rescue of human life or vessel, the other is concerning inference control such as meta-knowledge.

The knowledge is organized by binary decision trees. The use of a binary decision tree has made possible examination as follows:

- (1) lack of knowledge,
- (2) unit of knowledge,
- (3) correlation of knowledge.

During the development of the rules and rule sets, some rules have been modified to define the condition or embedded additional conditions in to achieve exclusion. It has been also necessary to set the level of priority on some rule sets and develop some rules to resolve the conflicts of rules.

a. Collision avoidance knowledge base. The knowledge base for collision avoidance is mainly composed of knowledge source which bear on an appraisal of risk. To make an objective appraisal of a collision risk level, two knowledge sources are used, one is the source by the rule-of-thumb and the traffic law (Regulations for Preventing Collision at Sea), and the other is the source using the value of TCPA (Time Interval to the Closest Point of Approach) and DCPA (Distance at the Closest Point of Approach). The knowledge base contains about 200 production rules.

b. Coping with collision accident knowledge base. The functions of coping with collision accident and collision avoidance knowledge base are classified into 14 functions as Fig.4 shows, according to the collision phenomena. Two coping functions which are as follows are selected as theme of research, because these functions contain a lot of heuristic experience.

- (1) The first coping with ship abandonment.
- (2) The second coping with ship abandonment.

The knowledge base contains about 100 production rules.

c. Engine operation knowledge base. Engine operation functions are classified nine categories as follows: preparation for engine, warming-up, starting, operation, observation, cooling-down, trouble diagnosis, repairing and emergency operation. The authors select three categories as the theme of research in relation to engine operations at the central control station. These are daily operation, observation and emergency operation. In accordance with these categories, the authors focus on the following situations.

- (1) Shifting to M0 watch and vice versa.
- (2) Coping with over torque.
- (3) dealing with the critical revolution.

An engine operation knowledge base which would be able to cope with these three kind of situation is constructed, because during these complicated situations, watch officers are required to make up sensitive judgement and decision in very short time.

The knowledge base contains about 170 production rules and about 30 meta-rules.

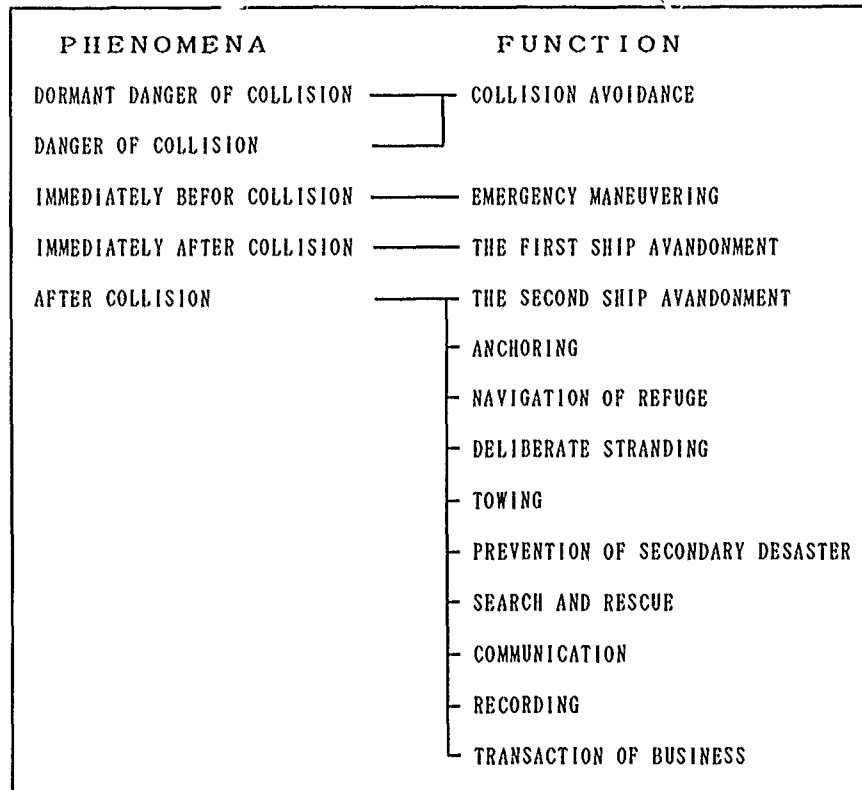


Fig.4 The Relation between Collision Phenomena and Coping Function

#### 4.3 Inference engine

An inference engine performs forward reasoning and backforward reasoning with the use of the rules in the knowledge base and the data in the working memory. Backward reasoning is mainly used in the collision avoidance sub-system,

forward reasoning is mainly used in the coping with collision accident sub-system and the engine operation sub-system.

The inference engine has been constructed with the following nine functions.

- (1) To read and translate the rules.
- (2) To request of input processing.
- (3) To prevent from asking the repetition data and the adversative data.
- (4) To perform numerical calculation.
- (5) To perform logical operation.
- (6) To perform relational operation.
- (7) To memorize a result of the inference and an inference process.
- (8) To perform undefined data processing.
- (9) To perform "why" explanation and "how" explanation.

#### 4.4 System operation

Diagram of the system action is shown in Fig.5. At first, an user inputs an initial data such as ship speed, course, engine revolution and so on. Then, the system recommends the processing item. If its item is accepted by the user, the system commences to search the relevant rule. The user may reject the recommended item and choose another. In this case, the system also searches the rules which satisfies the item choosen by the user. The system requests for input if it is necessary. At this time, the user has response by input of appropriate answer. The user may select the "why" explanation and the "how" explanation if necessary.

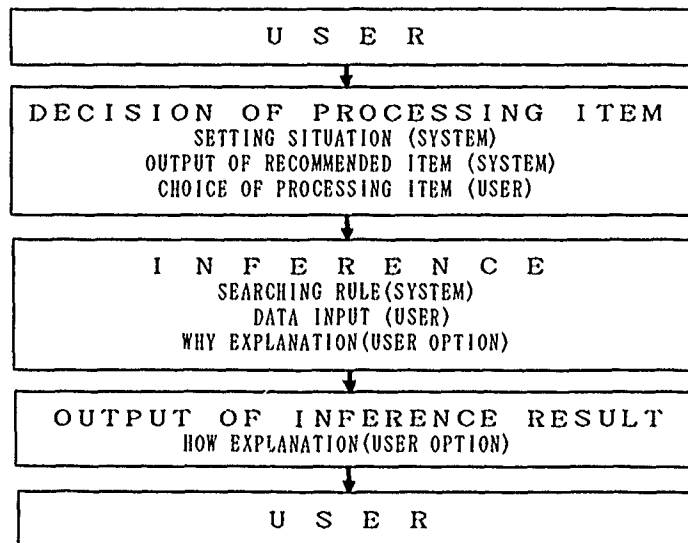


Fig.5 Outline of the System Procedure



## 5. SYSTEM VALIDATION AND EVALUATION

### 5.1 System Validation

System validation concerns that the correct problem was solved, and it is equivalent to assay a system capacity. The three sub-systems have been exercised within a wide-ranging series of test situation aimed at discovering ways to make the system fail. Test situations are separated into two groupes, one is simulation condition according to scenario which use a hearing from experts, and the other is simulation condition that is a little different from a scenario.

The system has been tested by the experimental simulations. Some examples of the output in Japanese are shown in Fig.6 (a) and (b). Fig.6 (a) shows that the user selects the recommended item and the system starts to ask a question to the user. Fig.6 (b) shows the result of an inference. This is a part of the simulation of the system for engine operation.

In spite of modifications and correlations of the rules extracted from captations, navigators and engineers, the informations or recommendations from the expert system have agreed approximately with their decisions. However there are some discordances. Such discordances happen especially on the problem that need timely information and require a speedy solution.

システムの推奨は「運転監視機能(EK)」に関するルールです。

=> つぎに検討したい内容を記号で選択し、入力してください。

運転準備機能	.....	EP
始動準備(暖機)機能	.....	EH
始動機能	.....	ES
運転機能	.....	EO
運転監視機能	.....	EW
停止(冷機)機能	.....	EC
故障診断機能	.....	ED
機器修理機能	.....	ER
緊急操作機能	.....	EE
選択すべき事項がわからない場合	....	un
終了する場合	.....	quit
.....	eo	

=> 入出港中ですか ?

「はい」の場合	.....	yes
「いいえ」の場合	.....	no
不明の場合	.....	un
質問理由を知りたい場合	.....	why
.....	yes	

Fig.6 (a) An Example of the Output

```

=> 今後十分な行き脚確保が可能ですか ?
    「はい」の場合 . . . . . yes
    「いいえ」の場合 . . . . . no
    不明の場合 . . . . . un
    質問理由を知りたい場合 . . . . . why
    . . . . . no

推論結果をつぎに示します。
***** EMERGENCY-RUN検討 *****

=> 推論過程を示しますか ?
    過程を示すばあい、how と入力ください
    そのたの場合、" RETURN-KEY" を押してください
    . . . . . how

EMERGENCY-RUN検討 は 次の結果から導かれました
入出港中である は 入力されました
および
増速中 は システムの内部処理により入力されました
および
危険回転数の通過の可能性あり は システムの内部処理により入力されました
および
今後十分な行き脚確保が可能でない は 入力されました

```

Fig.6 (b) An Example of the Output

## 5.2 Prediction of system size

A building knowledge base consists of following five phases:

- phase 1 : studies in literature,
- phase 2 : knowledge acquisition,
- phase 3 : translation of knowledge,
- phase 4 : classification and adjustment of the rules,
- phase 5 : implementation.

Total working time needed to build a knowledge base is obtained based on the experience of building three sub-systems. And working ratio which means working time in each phase to total working time. Table 1 shows the ratio of working time. A number of days which have spent accumulation of one modified production rule by one person are about 0.8 days in knowledge from experts' expertise, about 0.36 days in knowledge from literature.

System size of an expert system for navigation at sea is predicted that the authors make an estimate of a number of production rule of expert sub-systems. As a result of careful discussion, if the expert system has a knowledge base management sub-system, about 2700 production rules are necessary for the knowledge base of the expert system for navigation at sea. The time

needed to build a full knowledge base of the expert system for navigation at sea by one person is roughly estimated to at least about 2000 days in regard to the only experts' expertise, about 1000 days in regard to the only literature's knowledge.

Table 1. The Ratio of Working Time

	EXPERT'S KNOWLEDGE	LITERATURE'S KNOWLEDGE
PHASE 1	14 %	31 %
PHASE 2	14 %	0 %
PHASE 3	14 %	23 %
PHASE 4	48 %	23 %
PHASE 5	10 %	23 %

### 5.3 System evaluation

a. Purpose of evaluation and evaluation technique. Evaluation of an expert system is an important step in an expert system development, whether informal or formal. Evaluation enables a feedback process to take place whereby the comments are served as a basis for iterative refinements of an expert system. However, it is still a problem that how to evaluate an expert system even today. In order to perform the evaluation of an expert system, it is necessary to establish these: purposes of evaluation, items for evaluation, criteria for evaluating and synthetic evaluation technique. Furthermore, in order to perform the synthetic evaluation of an expert system, it is needed that hierarchical classification of evaluation items and settlement of the priorities of evaluation items in each hierarchy.

According to Gashning et al. <sup>(1)</sup>, expert systems are evaluated primary to test for program accuracy and utility. In this paper, the purposes of evaluation are:

- (1) to test for system accuracy,
- (2) to test for system utility,
- (3) to test for system realization.

The third purpose is the most significant for development of the expert system. The engine operation expert sub-system is chosen as the principal subject of the evaluation, because it is improved a user interface function.

Evaluation items shown in Fig.7 are consist of the first hierarchy items and the second hierarchy items. On each evaluation item, more than one evaluation criteria is derived by the use of software quality evaluation technique. An example of the evaluation criteria is shown as follows:

Accuracy:

- (1) its output is sufficiently precise to satisfy their needed use,

- (2) accumulated knowledge agrees well with expert's knowledge.
- (3) inference process agrees well with expert's inference process.
- (4) inference result agrees approximately with expert's inference result.

Affinity with operation:

- (1) system procedure can be closely connected with operation procedure.
- (2) purposes and the domain of support are cleared.
- (3) operation's efficiency is improved by using the expert system.

It is necessary that a set of evaluation items and criteria are mutually exclusive and exhaustive, and also necessary that a construction of evaluation item is a hierarchical structure. Therefore, it will be easy to use the refinements of the expert system as the evaluation results. These evaluation items and criteria cover the important consideration for evaluation purposes, namely, accuracy of the methodology, needed resources, easy to use and easy to maintain.

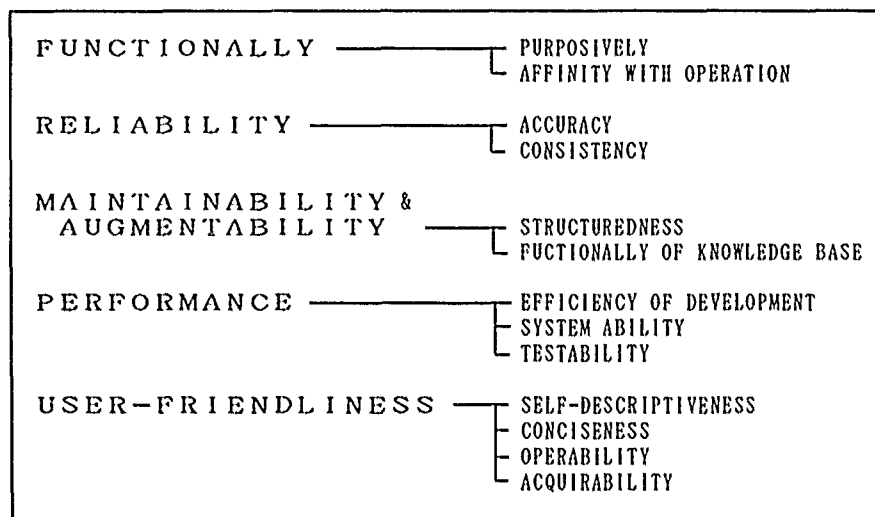


Fig.7 Evaluation Items

Synthetic evaluation value  $F$  which is defined a weighted arithmetic mean of evaluation value in each hierarchy can be calculated easily using the following equation.

$$F = \sum W_j (\sum w_i e_i)_j$$

$$\text{where } \sum w_i = 1 \text{ and } \sum W_j = 1$$

$e_i$  is an evaluation value to the second hierarchy evaluation items, and it has five levels.  $w_i$  and  $W_j$  is the priority, and it is the first and the second hierarchy evaluation items respectively. The priorities of evaluation items are

decided by the delphi method which summarize all opinions of the experimental subjects.

b. Experimental evaluation. Experimental subjects composed by five men are chosen from following three categories:

- (1) ship operator who has rich business experiences,
- (2) a man who will become a user of practical expert system in the future,
- (3) a man who is concerned with system development including knowledge donor.

Experimental evaluation is performed after the system purpose and contents are explained to experimental subjects. And system operation is demonstrated to them.

Evaluation data is obtained from debriefings and questionnaire. A purpose of the debriefing is mainly investigation of an ideal form of expert system for navigation at sea and user interface of its system. The debriefing is performed about following items:

- (1) system operation and system action,
- (2) function of a knowledge base,
- (3) possibility of the on-board system,
- (4) needs of utilization in ship operation.

Furthermore, some items which result in the concrete evaluation criteria are investigated. As a result, it is clear that system response time which is defined a time required between initial request and final out put of inference result must be took within 1 minuite. It is also clear that computer response time which is defined a time required between request and answer must be took within 1~2 seconds in case of emergency, within 5~6 seconds in case of normalcy.

Generally speaking, a result of questionnaire is easily influenced by a question contents. The authors tried as hard as possible to finish a written inquiry which consist of impartiality and unprejudiced questions.

Questionnaire for user interface are performed about following items:

- (1) display format,
- (2) operation guidance,
- (3) system control,
- (4) system action,
- (5) general impression.

The evaluation form is consist of about sixty questions which developed items for investigation. An answer to the questionnaire needs an evaluation value which has five levels and a piece of advice in the form. A great deal of advice which are very useful for developing expert system is obtained by questionnaire.

The authors make a synthetic evaluation form with reference to the debriefing result and the questionnaire. The synthetic evaluation form is made up of hierachical evaluation items, the evaluation criteria and the evaluation value which has five levels.

c. Evaluation result and discussion for user interface. A typical example of the questionnaire for user interface is shown in Fig.8. Fig.8 which is shown by star diagram makes it easy to understand the general tendency. Although satisfactory result of the general tendency is obtained, the result of evaluation level is not satisfied. Especially, the evaluation level of the system operation is lower than that of other evaluation item. This is caused by

standardized user model. It is necessary that the user interface system which the user can change computer response message easily. Furthermore, an introduction of the artificial intelligence technique like the speech recognition is necessary for improvement of synthetic evaluation value.

The visual sensation is used to look-out, and the motor sensation is used to the operation of the maneuvering equipment. But the auditory sense and the faculty of speech of operator are not very used to ship operation in bridge. It is necessary to develop an enhanced system which cover voice input / output in the future.

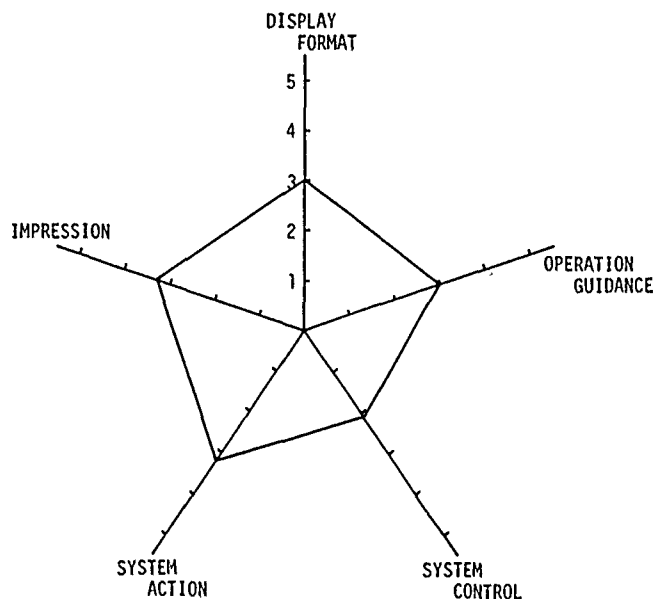


Fig.8 Evaluation Result for User Interface

d. Evaluation result and discussion for synthetic evaluation. The synthetic evaluation level is shown in Fig.9. The coordinates of Fig.9 are corresponded to the first hierarchy evaluation items. The general tendency agreed approximately with the purpose of sub-systems development. It is as same as it that the authors have already expected. It means that the evaluation method is suitable for the expert system.

The synthetic evaluation level of collision avoidance expert sub-system, coping with collision accident expert sub-system and engine operation expert sub-system is 2.75, 2.90 and 3.74 respectively. Sufficient results which are possible to show the validity of construction and selection of evaluation items are obtained.

Further investigation from these two point of view is needed, one is improvement of the inadequate function on basis of evaluation results, the other

is the development of evaluation system which can be considered evaluation opportunity. The evaluation method and evaluation items proposed in this paper will give an instruction of the evaluation process.

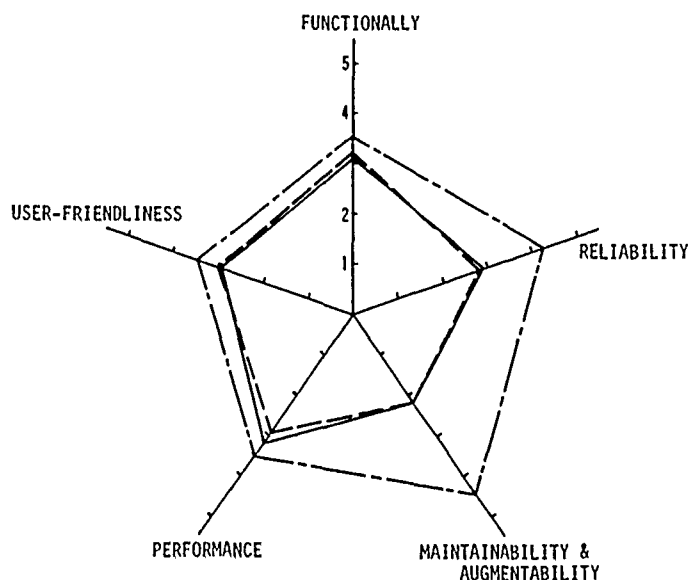


Fig. 9 Synthetic Evaluation Result. A solid line, a dashed line and a dash-dotted line represents the evaluation level of the coping with collision accident expert sub-system, the collision avoidance expert sub-system and the engine operation expert sub-system respectively.

## 6. CONCLUSION

The authors were investigated the expert system for navigation at sea on basis of development of three expert sub-systems. And sufficient results and very valuable information for developing an expert system point of view were obtained. Trial and error verification studies should still be performed when evaluating an expert system, but the evaluation method and evaluation items proposed in this paper would give an instruction of the evaluation process.

The summary of the analysis of experimental simulation and evaluation results are shown below.

- (1) The output of the system is useful for the captain's or ship operators decision making.
- (2) Activities of these systems agree well with the rule of thumb.
- (3) Except an emergency, system response time satisfies ship operators requirement.
- (4) This expert system has a practical use in ship operation.

Although satisfactory results are obtained, there are many problems which have to be solved. Further investigation from these three point of view is needed for reaching the stage for practical use.

- (1) development of knowledge base management system.
- (2) reduction in inference time.
- (3) repletion of user interface.

The authors think that this field of study will be steadily developed step by step, not rapidly. And trial and error are an inseparable part of technical development. The authors will be glad if our paper is any help to the people concerned.

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## "KNOWLEDGE BASED SYSTEMS" - THE PRACTICAL REALITY

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### ABSTRACT

Over the last few years we have seen the increasing development of knowledge based computer programs and expert systems in shore based applications. However, this technology has been slow in being recognised and developed in the marine industry.

Unlike numerous papers in the past which have either described specific expert systems or discussed the technical specifications of such programs, this paper examines the various considerations that need to be addressed so that knowledge based and expert systems can play a practical role in vessel operations. With the ever increasing complexity of systems, particularly with control systems, and with reduced manning levels being imposed upon operators either as a way of reducing costs or as a result of demographic trends, do such systems really offer us help or are they a hindrance? This paper will attempt to offer an answer.

Reference is made in the paper to an existing expert system. The lessons learned during the development and the use of this system are discussed and used to define the characteristics needed in such systems to ensure that they are of practical value in the field.

The potential application of expert systems may be enormous but one has to be aware of their limitations as well as their present and perceived values. In the author's view the future application of such systems will require an even greater awareness. It may well turn out that, given the development of true artificial intelligence, the present expert systems will be given its true position in the history of technology - a position firmly in the past. The intelligent knowledge based system may then come to the fore.

### 1 INTRODUCTION

#### 1.1 THE INFLUENCE OF SOCIAL AND TECHNOLOGICAL TRENDS ON THE DEVELOPMENT OF KNOWLEDGE BASED COMPUTER PROGRAMS AND EXPERT SYSTEMS.

Although social demographic trends vary from country to country there are still a number of underlying trends which have to be addressed. Of

particular importance to the marine industry is the decline in the traditional source of recruitment. This has come about as a result of changes in the age profile of the work force in various countries, the increased number of women in the work-force with a "relative" decline in the number of men, and the change of emphasis in education programmes in many countries away from the sciences towards the arts. Such trends have a "knock-on" effect in that there is a serious shortage of experienced manpower available at the present time which unfortunately is a trend which is not likely to be reversed in the near future.

Rapid technological developments have been made in the last decade and this trend is snowballing. Technological change is generally accompanied by increased plant and control system sophistication and complexity which means that staff required to operate and maintain such equipment have to be highly trained and motivated. Training in a rapidly changing environment has to be developed at the same rate, or perhaps faster, than the change itself. Training is therefore a very expensive operating cost.

These two trends would appear to be pulling in opposing directions yet both present the ship manager with significant problems. There are of course a number of solutions that can be used to counteract these trends the majority of which will cost the manager more money or reduce his commercial or military effectiveness. One has to recognise that such social and technological trends are not new; we live in an ever changing environment and therefore the task perhaps is to be able to bridge the "gap" and survive until the next social or technological wave comes. Knowledge based computer programs and expert systems perhaps present us with a tool to achieve this.

## 2 KNOWLEDGE BASED COMPUTER PROGRAMS, EXPERT SYSTEMS OF ARTIFICIAL INTELLIGENCE?

Many interesting and commendable technical papers and articles have been written in the past on expert systems, knowledge based systems and artificial intelligence, which have contributed significantly to the general awareness of the value of such systems. However, each of these terms refer to different aspects of knowledge engineering technology and therefore it is worth clarifying these terms to alleviate any possible misunderstanding that may exist.

### Expert Systems

Are a means of making available to non-experts a database of expert knowledge, e.g. initial diagnosis of medical ailments or a comparison of legal precedent. In expert systems the input of knowledge from the expert is based on the expert's opinion and experience.

### Knowledge Based Systems

A means of making available a set of well established rules and factual knowledge to the end user who may not be

familiar with the subject. Such systems differ from expert systems in that they do not contain experience related data or opinions. An intelligent knowledge based system is defined as a knowledge based system with elements of artificial intelligence which allow it to learn from reaction to its own responses and thus build up an increasing data base of knowledge.

Artificial Intelligence - A term used to describe the use of computers in such a way that they perform operations analogous to the human abilities of learning and decision making thus giving such computer programs a "self-learning" capability. A term often used to embrace expert systems, knowledge based systems and decision support systems, although strictly speaking none of these requires a "self-learning" capability. A much over used term.

There are, of course, other variations of these definitions.

In practice, there can be an overlap between expert systems and knowledge based systems in that some expert systems utilise characteristics of knowledge based systems. Unfortunately, in some cases this has also gone to the extreme where so-called expert systems are just simple "factual" knowledge based systems. Let us discuss in more detail the difference between these two technologies and analyse the practical significance of these differences in terms of the suitability to the marine environment. This can best be demonstrated by considering a practical example.

In the area of condition monitoring, the application of knowledge based systems and expert systems can be of real practical value. A knowledge based system incorporated into a vibration condition monitoring program for example would be able to indicate when the acceleration force of a particular component reached a preset limit, then the inherent relevant rule in the program would indicate to the operator to reduce power so that the vibration levels are able to fall below this predetermined value. However, with expert systems more information can be imparted to the operator by saying that with vibration at point "A" reaching a predetermined limit, or rising at a predetermined rate, and with vibration at another point adjacent to it, say at "C", also having increased, then by experience the potential cause of the vibration can be pinpointed and the operator advised of any appropriate action to be taken rectifying the source of the problem as soon as possible.

The knowledge based systems are, therefore, of practical use where the relationships between elements are preset by well established relationships

and where set procedures have to be followed. Expert systems allow greater flexibility of application, however, they do have the potential shortfall that any inherent experience or opinions, if not correct or if not written into the program correctly, can lead to the incorrect action being recommended and taken by the operator.

It is clear, therefore, that the application under consideration for the application of a knowledge based system or an expert system has to be clearly defined at the onset and that the requirements from the operator with regard to safety, security, as well as efficiency of the operation being controlled has also to be taken into consideration.

The practical advantage of knowledge based systems is perhaps more relevant in combination with other software packages such as spare gear inventory control software programs where, if the inventory of a specific item in the stock reaches a minimum level, then the knowledge base will inform the operator how, when and where to order the stock item required. Other applications for knowledge based systems are as follows:

- Ballast control systems.
- Ship loading programs.
- Administration procedures.
- Management accounting tasks.
- Reference to existing data bases; Design rules.
- Classification rules.
- Other existing legislation.

In general, knowledge based systems are of value where routine information is required from predefined data sources where procedures have been predetermined. Knowledge based systems enable time consuming tasks to be undertaken more quickly and accurately.

Another variation on knowledge based systems is the intelligent knowledge based system. Such systems utilise artificial intelligence techniques which implies that they have the ability to learn and generate new knowledge. Computer programs with a "self learning" capability are very much still at the research stage and are hence a long way from practical use in the field. The implications of a "self learning" capability brings with it numerous questions regarding suitability, integrity of knowledge etc. which all have to be addressed and considered in the light of individual applications. Since practical systems of this nature are not yet available this paper will not comment further upon them.

### 3 EXPERT SYSTEM ARCHITECTURE AND LIMITATIONS

The potential of expert systems is enormous and can cover a multitude of functions as well as interfunctional applications in ship operations. But before we consider the practical application of such systems, let us first examine clearly our fundamental need, or otherwise, for such systems. From this basis, we will therefore be able to identify areas of application as well as some of the fundamental characteristics of the systems to be used.

Some of you may be familiar with expert systems, how they are developed and their limitations. Indeed, some of you may be considering using such systems, but are such systems going to fully satisfy your objectives both now and in the future? For those of you who are relatively new to such technology, the message in this paper is that such systems do not have to be viewed as highly complex computer programs that remain the domain of relatively few "experts" or academics. With careful logical planning at the early stages of selecting and developing such systems, the mystique falls away.

An expert system is a computer program created to solve problems in a particular domain, they do not have any built in learning capability. A domain in itself is a specific area of interest to which an expert system can be applied by utilising the knowledge relative to experience and opinions obtained from experts in that domain. To make an expert system of practical value, we have to mimic the way people think about a particular problem and how they arrive at making decisions and analyse the facts to solve the problem. This is achieved by utilising four essential steps:

- (1) By identifying and setting a specific goal towards which our thought processes travel.
- (2) To collect all the relevant facts applicable to the specific objective, and to correlate these facts together to help us reach, via a consultation with the program, the specific goal.
- (3) For any expert system to be effective and efficient, an element of pruning of the various facts is required.
- (4) The final process is to use an inference mechanism and heuristic rules to infer from the remaining facts the results, conclusions and opinions and advice of the expert.

The key elements of any expert system are therefore goals, facts, pruning, inference mechanism and heuristic rules which collectively mimic the human decision making process. This can be shown diagrammatically in Figure 1.

We have mentioned the term "heuristic rules" and these form an essential part of any expert system. Heuristic rules are not formulated as a result of factual knowledge, but are rules that only an expert would know through experience in his specific domain. The heuristic rules used in any expert system must be based on sound, safe, "logical" operating experience, since the integrity of such rules are the keystone to the validity of any expert system and from this view point it is essential to consult a number of experts in different disciplines.

Communications between people and computers is an area in which a considerable amount of research is now being done. The terms "interfacing" and "user friendliness" are widely used and the importance of these aspects is fundamental in the use of expert systems. The key element in any expert

system is therefore the ability of a person to converse with the computer program in a similar manner that he would do with an expert in the domain being analysed. This means that the operator should be able to explain the situation clearly to the computer program and define the task that the program is required to do and, in return, the computer is required to respond in a clear concise manner with well reasoned logical questions, solutions and advice. Unfortunately some expert systems fall short of such a requirement.

Expert system technology is a new and rapidly changing one and will play an increasing role in today's technological environment. However, the cost and benefits associated with such programs will vary depending on the role to which such programs are put to use and how the programs themselves are developed. These implications need to be considered very carefully, since expert systems are not suitable to all applications and hence lessons should be learnt from already developed programs. What is important, however, is recognising their limitations, this being just as important as the correct selection of potential applications. The limitations of expert systems can be summarised as follows:

- (1) The programs are only as good as the experts and the programmer.
- (2) Expert systems ADVISE, they do not control!
- (3) Unfortunately there can be the temptation to place too much reliance on the advice given by an expert system without fully understanding the significance of the advice given. (This can also be the fault of bad design and poor operation.)
- (4) The weakness of "real-time" expert systems is in the reliability of the sensors used to provide the initial data.
- (5) Since expert systems utilise knowledge based on opinions and observations, then such systems are not suitable for "on-line" applications to automatically control important plant processes etc. This is really the function of knowledge based systems.

These points are clarified in more detail later in the text.

#### 4 APPLICATION OF EXPERT SYSTEMS

Expert systems are ideally applied in areas where specialist knowledge is needed above that normally required for general operation. It is essential that the knowledge data base used in expert systems is based on sound, safe and practical knowledge and that the experts formulating such a data base are in agreement with such knowledge. For an expert system to be commercially attractive, it has to satisfy one fundamental objective, i.e.

to save the operator money. Therefore, areas where improvement in operational, service or financial gain can be made, are ideal applications for such systems.

However, not all tasks can be ideally addressed by the use of expert systems. The following simple checklist will help us to evaluate the suitability of an expert system in particular applications:

- (1) If the difficulty can be solved by utilising conventional computing tools, or conventional approaches to solve the difficulty then the utilisation of an expert system is not cost effective unless the prime criteria is time. In such cases knowledge based systems are warranted.
- (2) The problem area should be one where local knowledge is not enough but where expertise is available but remote from the location of the difficulty.
- (3) If there is a need to explore a number of alternative solutions and address them rapidly, then an expert system is viable.
- (4) Sufficient knowledge must be known about the subject and experts must exist.
- (5) A typical consultancy session with an expert system should be able to solve the difficulty within a short period of time (10 mins.)

Expert systems are ideally utilised where there is a need for diagnostic analysis; as in the case of localising a fault in an electronic circuit or a sophisticated control system. Expert systems can provide an important role in acting as advisers whereby specialist advice which may be held centrally is readily available to the local operator when needed. Our own experience in developing an expert system called SEAFUEL, which addresses aspects of handling, storage and pre-treatment of residual fuel oil on board a ship (Ref 1,2), has indicated that expert systems are a very powerful communications tool in that new developments, results of R&D investigations and experiences can be communicated to operating staff in a very practical and effective way.

One further very interesting application of expert systems is as an intelligent front end to other computer programs; particularly where large databases of information are held which have to be analysed and a quantitative assessment made of the problem. Expert systems directly linked to other operating programs, such as fault diagnosis and condition monitoring, are worth addressing in more detail since this is one area where maximum advantage can be made of such systems. Another example is in the field of vibration analysis. With reference to predetermined analysis trends, expert systems can interface with vibration analysis software programs to determine the rate of growth of vibration and therefore make recommendations with regard to the scheduling of maintenance work between standard maintenance stops, if necessary, and to prevent expensive and

dangerous breakdowns which may occur as a result of any defect. This type of application of expert systems in today's highly technological environment is important, since such systems can monitor, interpret and diagnose work schedules automatically and, therefore, relieve the burden from the skilled engineer as well as enhance the safety, reliability and integrity of equipment.

Such "real-time" expert systems can be of specific application to the marine industry where there is a shortage of manpower, i.e. maintenance scheduling and voyage planning and where training requirements are high. "Real-time" expert systems can also be utilised where there is a very large, sophisticated information and control system with numerous inter-functional elements to be monitored. Such expert systems are already being utilised in large scale processing applications, such as power generation and within the cement industry. With such process systems, the operators knowledge and interaction with the monitoring system of the sophisticated plant is of key importance in not only recognising the significance of any alarm fault that can occur, but also with respect to the quick response to any potential dangerous condition that may develop. With the use of "real-time" expert systems, the user and the expert system can interact to monitor, diagnose and respond to specific plant information in the context of fault analysis much more effectively, particularly where a large plant is being monitored. However, the danger of such an application of expert systems is that the operator may pay too much reliance to the advice given by such programs who themselves may be misled by a faulty sensor signal. In this context, therefore, it is essential that any advice given by such expert systems should always verge on the side of safety. The advantages of such systems are obvious, in that the operator is always informed of the appropriate steps to take to avert or deal with potentially dangerous situations, as well as being provided with an on-line documentation of set safety procedures. Since the majority of accidents are due to human error expert systems can minimise such errors.

The potential of expert systems in such commercial applications is very high, particularly where the interpretation of numerous scenarios may be required on a continuous basis in order to enhance the safety, reliability, efficiency, effectiveness and productivity of various high capital cost manufacturing processes. To take such applications a step further, i.e. to close the control loop and interface the expert system with control functions, is not a practical reality since by definition expert systems are not based on factual knowledge but use heuristic rules. However, they can play a significant role in such applications by summarising the situation and advising the operator of the various courses of action that can be taken and the consequences of such action. The final responsibility must always be with the plant operator in conjunction with any built in safety functions.

Having decided upon a possible suitable application for an expert system the following management aspects must also be considered:

- Is the utilisation of the program cost effective?
- What does the end user expect from such a system?



- Are the experts available and who will be involved in the development of the program?
- Is it better to write your own program or to use an expert system shell, etc?
- Are you able to update the program in light of feedback and/or technological changes?
- Is there going to be a need to have some form of security to protect the data or knowledge base in the program?

##### 5 PROGRAM CHARACTERISTICS TO BE CONSIDERED WHEN BUILDING OR SELECTING EXPERT SYSTEMS

There are a number of essential requirements for expert systems if they are to act as a practical problem solving tools, rather than theoretical demonstrations of expert system programming techniques;

- (1) The first requirement is that such systems should be available in the field for the end user. For shipboard use the system should be self-contained so that it can be used on board a vessel independent of any land-based computer particularly where access to a land-based computer may be difficult or where communication with the central office may impose delays.
- (2) A "user friendly" expert system is essential to build confidence in the user. To satisfy this requirement, expert systems need to reflect the problem solving style of the end user, and because of the practical applications of such systems, the terminology used must be carefully tailored to suit the user as well as a the specific application. By using this approach few, if any, ambiguities or misinterpretations should result. A simple straight-forward logical approach is also essential in addressing any problem and this combined with a reasonable level of dialogue at a knowledge level the operator can identify with, will make such expert systems a valuable and an effective tool to use. The end user should be involved at the initial design stage of the program. If this element is not taken into account it is surprising how quickly the credibility of such programs are lost.
- (3) To enhance the practical value and the scope of application of expert systems, it is often desirable to be able to integrate different types of knowledge and information data into the expert system program. Mathematical calculations, factual databases, diagnostic rules, as well as the facility to diagrammatically represent data, are the main elements which should be able to be integrated into such programs. It is important, therefore, that the program language used and the structure of such expert systems, be able to address this requirement.
- (4) Expert systems by their nature may hold a vast amount of knowledge and inference rules and, therefore, the number of different scenarios that can be developed is enormous. It is,

therefore essential that expert systems are able to address such knowledge basis without being inconsistent, incomplete or unreliable in its response to similar inputs.

- (5) Expert systems should always be capable of providing diagnosis and recommendations throughout each consultation session at the command of the user thus enhancing the dialogue and confidence between the computer program and the operator.
- (6) Our experiences indicate that the most effective expert systems are those that offer very simple screen presentations to the operator. Such screen presentations can be menu driven and where advice is given, text on the screen should be clear, concise and uncluttered. (Figure 2)
- (7) To allow flexibility in the knowledge base used by an expert system, the knowledge base should be constructed of a number of individual accessible modules, known as sections. In diagnostic expert systems, it may be possible to relate these sections to major mechanical systems, the sub-systems and associated types. Being able to analyse the problem via the use of these modules will greatly aid disciplined software development and program testing. (Figure 3)
- (8) The ability of such expert systems to store and display large quantities of textual material in an interactive manner increases the usefulness of the program as a training aid.
- (9) The ability to integrate new system commands in the expert system at the building stage of the program is also an essential requirement. Such system commands could be used to display graphical data, to move around the textual data screens, to change input data during the course of the consultation session, or to call advice from the expert system at any part of the consultation session. With this facility, it is possible during the construction of the program to tailor the program to meet the special requirements that are required for the specific practical problem solving expert system application being considered.
- (10) We have mentioned a need for expert systems to have a clear, unambiguous dialogue with the operator and another essential element with this aspect is that when the computer program requires information the prompt screens presented to the operator for information should be unambiguous, composed of simple phrases/ sentences and ideally should not have more than two questions per screen. This simple approach allows the operator to use the program more effectively and efficiently, but at the same time does not confuse the operator with the importance of the questions being asked and thus he is able to follow the logic that the expert system program is following. At each input data prompt, the operator should be informed of the range of the data expected by the program; the input data being restricted to numerical or single word responses, as appropriate. This feature also allows validation of the input data to be easily made with the result that realistic scenarios are generated by the program.

- (11) All expert systems should have characteristics where they are able to justify the logic of their reasoning and in doing so appear to be complete in the understanding of the problem being experienced by the operator to the extent that the operator has full confidence in the knowledge held inside the computer program and, therefore, in the solutions being offered. To build this confidence the operator should be able to issue commands to the computer program so that he is able to clearly understand the problem being experienced and this, in turn, will help him to quickly identify the source of the difficulty being experienced.

Commands such as "HOW" and "WHY" should be embedded in the program so that the operator is able to call up these commands in response to a prompt screen from the program which may ask him for specific information; the "WHY" command effectively asking the computer program why the operator is being asked to input certain data and what relevance this data will have with the logic pattern that has been followed by the computer program, the "HOW" command will enable the computer program to explain to the operator how the input information helps the logic path to be developed further towards identifying the end conclusion. These two commands are fundamental to the enhancement of any expert system when used as a diagnostic tool and also makes the program ideally suited as a training aid.

The importance of this confidence building element cannot be overstated. To achieve this criteria, the skills of the expert as well, as the programmer, play a very important part and it is essential that this criteria is addressed at the very onset of any program development.

- (12) One very useful command is a "status" command, which enables the operator to call up a status report at any time during a consultation session. This latter feature is recommended for use at the end of each consultation session to draw up a brief report outlining the input parameters defined by the operator, the results of any procedural tests used throughout the consultation and the results of any logical conclusions drawn by the knowledge base. However, this command should also be able to be called up at any time during the consultation session and should be supplied as part of the underlying software. (Figure 4)

## 6 A TYPICAL CONSULTATION SESSION STRUCTURE

We have seen that expert systems are based on data and heuristic rules driven by an inference engine so that the expert system can form logical conclusions and observations in relationship to the specific domain in which the expert system was built. Good expert systems should have as a foundation a simple straight-forward logical approach to addressing the task. The basic logic steps in a typical diagnostic consultation session

can be summarised as follows:

- (1) The operator defines to the program, via suitable program "prompt" screens, where the problem has developed.
- (2) The operator again defines to the program, via suitable "prompt" screens, how the problem has manifested itself.
- (3) The program prompts the operator for more details regarding the operating parameters of the specific part of the system being addressed by the expert system domain.
- (4) Depending on a specific task being addressed, the operator then has a facility as any time during a consultation to call up a number of simple commands, such as information relating to procedural tests that may be required to be undertaken, to analyse any diagrammatical information, or to call up any other data integrated with the software program.
- (5) As the program progresses through the logic tree, from the top of the tree to the root source of the problem, the operator is continually prompted to input relevant data, as outlined above. It is also important that this dialogue should not be just one sided; the program should also inform and advice the operator as it passes through a consultation.

When the logic path in the expert system has been completed, the program will identify to the operator the potential source of the problem being experienced, in conjunction with an indication of the long-term effects of this problem on the particular application domain being addressed by the expert system. Finally, the recommended action to be taken in order to alleviate or eliminate the source of the difficulty together with the logical reason for such action, should be given by the expert system.

- (6) At the end of each consultation session, the operator is recommended to call up a "status" command in order to obtain a simple overview of the consultation session the operator has followed with the program.

The sequences of events are summarised diagrammatically in Figure 5.

## 7 CONCLUSION

Continued social and technological changes in the environment have a profound influence on the marine industry, particularly in the areas of recruitment and training. The development of the use of computer programs such as knowledge based systems and expert systems has accelerated rapidly and such computer programs can help us to minimise the adverse effects of such trends.

True artificial intelligence based programs are still in the research stage and hence are not ready for practical use in the field. Such programs will inevitably bring with them specific areas to be addressed before being fully acceptable for practical applications. However, "factual" knowledge based systems and expert systems are ready now for practical applications and both systems can play a significant role in marine operations. Expert systems and knowledge based computer programs have characteristics which make them suitable to different but specific tasks.

Expert systems are ideally suited to fault diagnosis as well as an enhancement of other computer programs. "Real-time" applications of expert systems such as interfacing with sophisticated, complex plant monitoring and control systems is an exciting application, but here again as in all expert systems the program will only be as good as the expert, the programmer and the end user. By definition expert systems are not suitable for "on-line" control applications.

Expert systems can also be used as an effective training aid in the field, thus endorsing shore based training in relationship to the specific ship application. During the development of our expert system SEAFUEL we identified a number of important aspects relating to the specifying, designing and the utilisation of such programs. These are discussed in the paper.

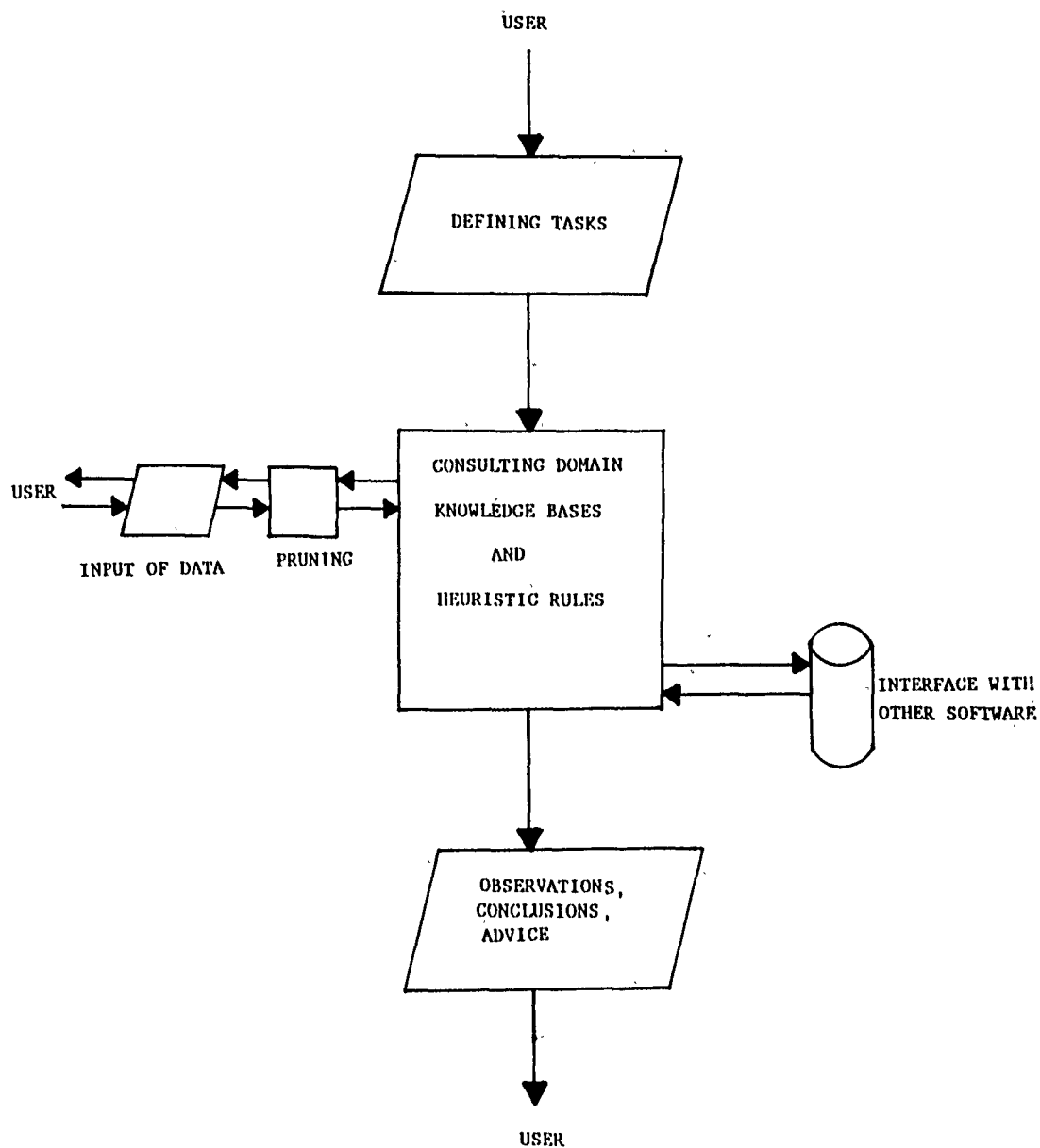
But what of the future? In the short term the wider use of knowledge based computer programs and expert systems is inevitable. Sophisticated but reliable control systems in conjunction with expert systems and well educated and highly motivated staff will enhance the reliability, safety, integrity, efficiency and effectiveness of marine vessels. Expert systems are only part of this scenario, but an exciting and as yet an under-utilised part. In the long term one can envisage the rapid and exciting development of true intelligent knowledge based systems which have the potential to bring with them revolutionary ideas in monitoring and control techniques.

#### ACKNOWLEDGEMENTS

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**FIGURE 1.** OVERVIEW OF THE ARCHITECTURE OF AN EXPERT SYSTEM.

GOAL: system

SECTION: control

-----  
In which part of the plant has the fault occurred ?

- (1) - Storage tank
- (2) - Centrifuge
- (3) - Filter
- (4) - Pump
- (5) - Heaters

-----  
Enter the number of the relevant entry : 1  
-----

FIGURE 2. SEAFUEL - MENU INPUT PROMPT SCREEN.

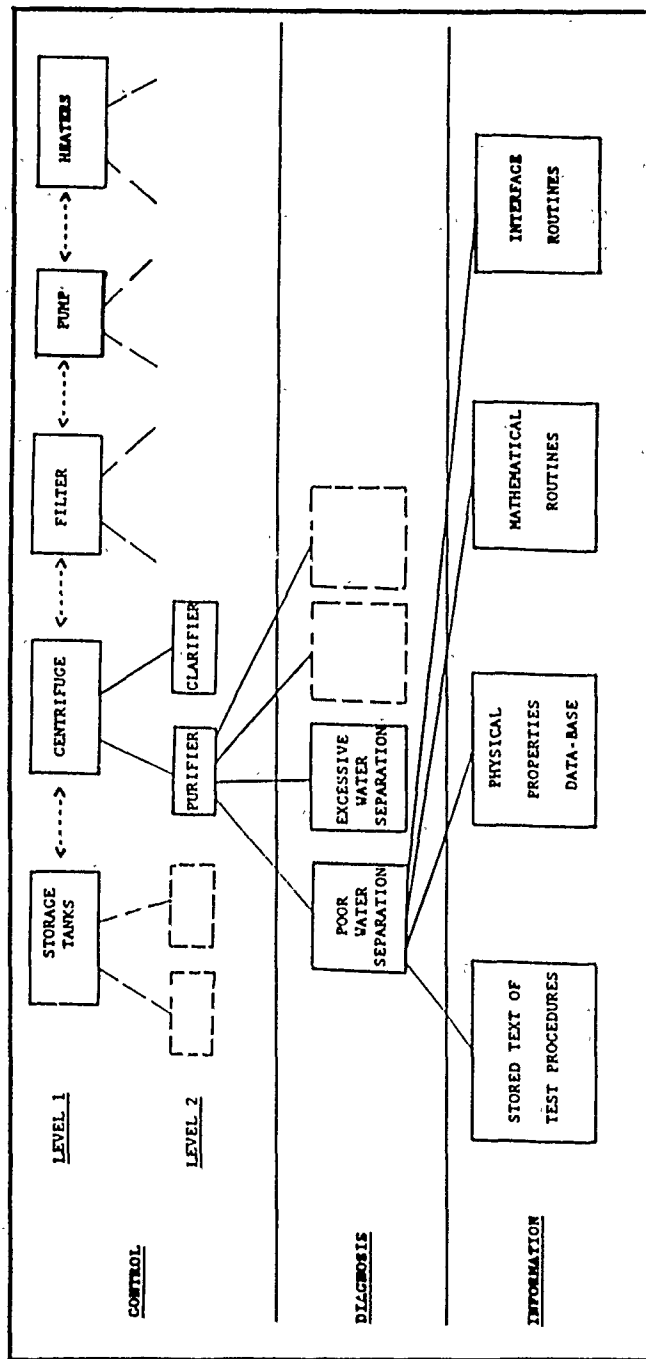


FIGURE 3. SEAFUEL - MODULAR STRUCTURE OF PROGRAM.



GOAL: finished                      SECTION: add\_info  
-----  
Current Status Of Established Parameters  
-----  
the part of the plant which has a fault (system) is 'store\_tank'  
the type of tank is (tank\_type) is 'bunker'  
type of problem occurring in the tank (tank\_problem) is 'pump'  
viscosity of the fuel oil (load\_viscosity) is '380'  
minimum temp for fuel to be pumpable (min\_temp\_visco) is '36'  
tank temperature (tank\_temp) is '50'  
Pour point of the fuel (pour\_point) is '-5'  
temp to which oil must be heated to restart flow (min\_temp\_pour) is '5'  
it is untrue that heating fuel has solved problem (hot\_fuel\_ok)  
the temperature above which wax is very unlikely (max\_temp\_wax) is '15'  
a sludge test has been performed (sludge\_test)  
it is untrue that the wax test is satisfied (wax\_test)  
it is untrue that the asphaltene test is satisfied (asphaltene\_test)  
the ship has experienced rough seas (rough\_sea)  
a high density BFO has been loaded recently (hi\_dens\_past)

-----  
LISTING STATUS OF CURRENTLY ESTABLISHED PARAMETERS  
PLEASE WAIT  
-----

PRESS ANY KEY TO CONTINUE

FIGURE 4. SEAFUEL - A STATUS REPORT IS AN IMPORTANT ASSET.

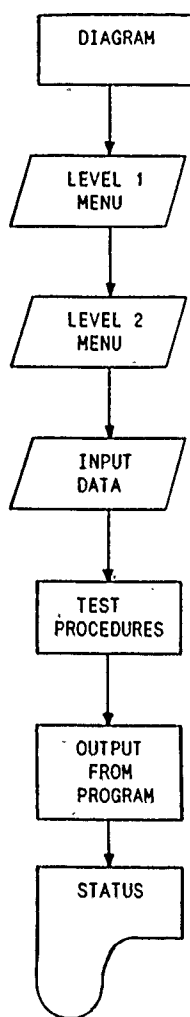


Diagram representation of system being addressed (useful addition if the program is being used as a training aid).

First stage of SEAFUEL consultation where the operator is prompted to identify where the difficulty is being experienced.

Second stage of data input. The operator is prompted to clarify, in more detail from a menu screen, the difficulty being experienced.

The SEAFUEL program prompts the operator for more data ie, fuel oil tank temperature, etc. This data is used to address the relevant information in the data bases, mathematical routines, etc.

The operator has the option to call up a number of fuel oil test procedures at any time during a SEAFUEL consultation.

The SEAFUEL program informs the operator of the source of the difficulty being experienced and the appropriate course of action to be taken.

A final status report of the above consultation is available during, or at the end of, each consultation.

**FIGURE 5. SEAFUEL - PROGRAM FLOW DIAGRAM.**

## FAULT IDENTIFICATION AND RESTRUCTURABLE CONTROL OF MARINE SYSTEMS

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### 1. ABSTRACT

This paper explores some possible applications to marine systems of fault detection and identification techniques combined with restructurable control methods. In particular, in the case of fault detection, statistical techniques are compared with an approach based on the rapidly growing artificial neural network methodology.

For the restructurable control problem, some concepts arising from aircraft control systems studies are utilized by exploiting the existing similarities with the dynamic behaviour of marine vehicles.

To illustrate the above methods we present some simulation results relating to multivariable control of hydrofoil craft.

### 2. INTRODUCTION

The need to improve efficiency and safety in the field of marine systems engineering, has stimulated during the last two decades an increasing use of automatic control techniques applied to the operation and automation of different types of marine vehicles (1), (2), (3).

The most common application is constituted by autopilots, which are devoted to the automatic control of the steering process of conventional surface ships during the three basic operative situations of course-keeping, course changing and track-keeping at a normal service speed. As it has been demonstrated by many simulation studies, sea trials and navigation data analysis, such devices are capable of assuring, if adequately designed and properly tuned, significant benefits in terms of reduced fuel consumption as well as of safety enhancement of merchant ships' operation.

Many challenging applications of automatic control techniques have been stimulated, moreover, in connection with the operation of

unconventional marine vehicles.

The class of these vehicles, which is going to become more and more wide in the near future, actually includes hydrofoils, hovercrafts, surface-effect ships, swaths, submersibles, etc. The dynamic behaviour of such crafts is generally characterized, if compared with conventional ships, by a higher cruising speed and also by an increased operability at lower speed.

A common feature of the above mentioned applications consists of a tendency towards increased automation of on-board functions, which should be carried out with a reduced interference of human operators.

For this purpose the on-board computer should carry out and integrate in real time a large number of complex functions, the most important of which are:

- guidance and control
- automatic navigation
- specific tasks

The guidance and control task generally consists of a feedback steering control strategy which, by using the available control devices, drives the vehicle through a desired trajectory. Quite often such a trajectory can be approximated by a sequence of way-points, which have to be reached navigating at a nominally constant speed, heading and/or depth.

The navigation task consists of determining at each time instant an optimal estimate of the vehicle's position, which is based on an integrated use of on board sensors.

Some specific tasks have also to be carried out, which are largely dependent on the application field and may be comprehensive of environment inspection, scenario recognition and understanding, manipulative and robotic activities, etc.

The correct and coordinated automatic execution of such functions, in the presence of various unpredictable disturbing events, is quite a demanding work. For this purpose, fault-tolerant techniques have to be incorporated into the algorithms which implement the different tasks.

This means that the successful operation of such systems is highly dependent on the availability of suitable processors which are capable of identifying faults in sensors and actuators, in real time, and can properly restructure the entire control systems in such a way to maintain adequate overall performance.

### 3. FAULT IDENTIFICATION AND RESTRUCTURABLE CONTROL

Most of the control system design methods which are generally used for carrying out the marine vehicles guidance and control tasks are based on the assumption that the underlying mathematical models are linear with perfectly known time-invariant parameters of the type:

$$\dot{x} = Ax + Bu + Gw \quad (3.1)$$

$$y = Cx + e \quad (3.2)$$

where  $x$  is a suitable state vector which contains the relevant information about system's dynamics,  $u$  is the control vector, while vector  $w$  is a stochastic process which takes external disturbances into account. The observation vector  $y$  takes into account the available measurements eventually corrupted by noise vector  $e$ .

It should be noted that the above model is quite often a very rough approximation of reality.

This possible discrepancy between a simplified model and physical reality gives rise to the exigence of designing control systems that are first of all robust with respect to parametric uncertainties. Among the possible candidate methods it can be shown that LQG (Linear Quadratic Gaussian) method exhibits acceptable robustness properties combined with the feature of retaining a number of classical engineering design concepts (4), (5).

### 3.1 Fault Detection and Identification

As already observed the discrepancy existing between the marine vehicles mathematical model and the real dynamical system, gives rise to the exigence of continuously monitoring the 'vehicle+environment+sensors+actuators' system in order to detect and point out any significant change in the equilibrium condition. Such changes may eventually be due to instrumentation faults, and, in this case, it is necessary to discriminate such abnormal situation from the many other possible ones.

If the control system is sufficiently robust and the navigation system is provided with a sufficient degree of integration, certain failures can be tolerated without modifications. Other failures, however, may be too severe for the normal mode controller to handle, and thus an active system modification is required.

A number of FDI (Fault Detection and Identification) algorithms have been proposed in the last decade, see for example Basseville (9) and Willsky (10), (11). The basic idea is to rely on a statistical decision test, as illustrated in Fig. 1. Such a test allows to decide, with a preset probability of false alarm, if a fault has occurred. A fault identification procedure can be subsequently initiated, which is based on the available information and collected statistics.

### 3.2 Restructurable control

In the presence of failures occurring in the system,

structural changes may appear in the controlled system mathematical model and, as a consequence of that, the global operation of the vehicle may irreparably deteriorate. In order to cope with this potentially very dangerous situation, it is necessary to globally reconfigure or restructure the control system according to the scheme shown in Fig.2. Given a failure of one or more control surfaces, for example, the objective of the reconfigurable control is to redistribute the control authority among the remaining active surfaces, in such a way that as much as possible of system performance can be recovered. In some particularly serious faults, it can be necessary to terminate the mission with a safe recovery of the vehicle. It can be shown (7), that LQG procedure can still be used for restructurable control design.

#### 4. HYDROFOIL APPLICATION

The FDI techniques combined with restructurable control will be applied to a surface-piercing hydrofoil craft.

##### 4.1 Hydrofoil mathematical model

With reference to Fig.3, the equations of motion representing the hydrofoil response to the control surface inputs, are written with respect to axes whose origin is at the center of gravity and in the reference condition of steady directed horizontally forward, the z-axis vertically upward and the y-axis to port.

The longitudinal motion is represented by the pitch angle  $\vartheta$  and by the C.G. height or heave  $z$ . The lateral motion is described by the sway velocity  $v$ , the roll angle  $\phi$  and the yaw rate  $r$ . Control is achieved by means of five control surfaces comprising four flaps and a rudder. The relative position, designation and sense of these surfaces is depicted in Fig.4.

According to (12), a linear mathematical model for the longitudinal motions of such a marine vehicle is given by a state space model of the type (3.1) and (3.2), where a state vector given by

$$x = (\vartheta \dot{\vartheta} z \dot{z} \phi \dot{\phi})^T \quad (4.1)$$

and a control vector

$$u = (\alpha_1 \alpha_2 \alpha_3 \alpha_4)^T \quad (4.2)$$

are considered. The control vector components are given by the four control surfaces constituted by flaps fitted in the fore and aft wings

Matrices A, B, C are of the type :

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ a_{21} & a_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & a_{43} & a_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & a_{65} & a_{66} \end{bmatrix} \quad (4.3)$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ b_{21} & b_{21} & b_{23} & b_{23} \\ 0 & 0 & 0 & 0 \\ b_{41} & b_{41} & b_{43} & b_{43} \\ 0 & 0 & 0 & 0 \\ b_{61} & -b_{61} & b_{63} & -b_{63} \end{bmatrix} \quad (4.4)$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \quad (4.5)$$

For simplicity, let us assume that the external disturbance vector  $w$  is absent and that the measurement noise vector  $e$  is constituted by independent gaussian white noises.

#### 4.2 Robust LQG Design

LQG control system requires that the control vector should be chosen, in such a way that the expected value of a quadratic cost function  $J$  of state and control variables is minimized with respect to the control vector  $u(t)$ :

$$J = E \int_{t_0}^{t_f} (x^T(t) Q x(t) + u^T(t) R u(t)) dt \quad (4.6)$$

Different types of situations can be easily managed by a proper choice of the weighting matrices  $Q$  and  $R$ . If it is assumed that  $t_f \gg t_0$  then a computationally simpler problem can be solved, which supplies a linear feedback of the type:

$$u(t) = -K \hat{x}(t) \quad (4.7)$$

where the matrix  $K$  is obtained by solving a time-invariant Riccati

equation, while  $\hat{x}(t)$  is an optimal estimate of the state vector  $x(t)$  supplied by a Kalman filter:

$$\dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t) + H(y - C\hat{x}(t)) \quad (4.8)$$

According to Doyle (4) and Safonov (5), a passive fault-tolerant control system design can be obtained by improving robustness with respect to uncertainties in the craft's dynamics as well as to external disturbances. This result can be achieved by a multivariable frequency domain shaping which reduces the controller sensitivity to uncertainties by a proper choice of the weighting matrix  $R$ . In such a way the nominal controller is passively robust with respect to small changes, which are most difficult to be detected, and therefore it allows to take into account only large changes due to system failures.

#### 4.3 FDI and restructurable control simulation

A simple application of the FDI and restructurable control techniques to the hydrofoil craft has been simulated. For this purpose, a robust LQG design has been first of all determined on the basis of the hydrofoil coefficients reported in (12) and by assuming that only the measurement noise vector is present and that the weighting matrices  $Q = \text{diag}(1)$  and  $R = \text{diag}(.1)$  are given.

In Fig.5 the transient responses of the controlled system following a non-zero initial condition are shown. The time histories of the four flaps angular deflections, of the three output variables (pitch, vertical speed and roll) and of the related innovations are given. Such plottings are obtained in normal mode operation, i.e. when all the sensors, actuators and vehicle's dynamic behaviour are operating in nominal conditions.

In Fig.6 there are shown the corresponding responses under the assumption that a fault occurred at the fore flaps, after 1.5 seconds. As it can be noticed in Fig. 6.3, the fault can be easily detected by examining the innovations of the output variables determined by the Kalman filter estimator.

The 'after the failure' mathematical model is obtained by simply modifying matrix  $B$ , on the basis of the information supplied by the FDI module. On correspondence with such a new model, a new couple of weighting matrices are chosen in order to maximize the performance of the remaining control surfaces. An algebraic reconfiguration procedure is used, according to (7), which involves the solution of a new Riccati equation. As it can be observed by comparison of the output variables shown in Fig. 5.2 and 6.2, the degradation of control system performance results to be quite small.

#### 5. USE OF ARTIFICIAL NEURAL NETWORKS IN RESTRUCTURABLE SYSTEMS

The use of Kalman filtering and restructurable control can be



efficiently applied to relatively simple situations, where statistical decisions about faults do not result to be too complicated. It should be noted, however, that there is a number of important situations in which a large number of sensors and actuators information have to be integrated for control, navigation and other specific tasks. Such situations mainly occur in the field of unmanned autonomous robotic vehicles and complex off-shore operations. It seems interesting to explore, in all such cases, the applicability of a recently proposed approach based on neural networks.

### 5.1 What are Artificial Neural Networks?

Artificial neural networks are highly abstract models of real nervous systems. It was in the late 19th century that it was first established that the neuron is the basic unit of the nervous system (15). Each neuron can be thought of as a simple processing element which receives and combines signals from many other neurons and, depending on the synaptic strength of each input, the neuron will, in turn, activate or inhibit the "firing" of the other neurons it is connected to. The brain consists of billions of such neurons, densely interconnected, and forming a massively parallel network of processing elements. The idea of artificial neural networks is based on an analogy with the brain's functional properties and its characteristic of parallelism. There are three main elements in the neural network models considered in the work discussed here, namely,

- a) Artificial Neuron Modelling and the Processing Rules
- b) Network Topology
- c) Learning Rules

#### a. Artificial Neuron Modelling and the Processing Rules.

Fig.7 illustrates the basic architecture of the artificial neuron model. Each neuron has many inputs which originate from the outputs of other neurons and are linked via connections of variable strength of weight,  $w_{ji}$ , which determine the effect of the transmitting neurons on the receiving ones. All these inputs are combined by some form of arithmetic operation, usually a simple weighted sum, to produce the net input. The output,  $y_j$ , is a function,  $f$ , of this net input. The nature of the output or activation function has a profound effect on the overall properties of the model. Three particular activation functions in common use are shown in Fig.8 where the output,  $O$ , is given as a function of the input,  $I$ , the weighted sum of the activations.

b. Network Topology. A neural network is composed of many nonlinear computational elements interconnected to one another in some pattern of connectivity. In general, they are arranged in layers as shown in Fig.9. Input neurons are those which receive

direct input signals from the outside world while output neurons are those that return the processed information. The hidden units in the intermediate layers are those whose inputs and outputs are internal to the network and are not "visible" outside. It is this pattern of connectivity that determine the functionality of the system.

c. Learning Rule. The architecture of neural networks offers a basis for learning the essential features of a system under investigation. Learning in neural networks is divided into three broad classes: supervised, reinforcement and unsupervised learning and the details of the method studied in this work is discussed later.

## 5.2 Why Neural Network?

The neural approach to computing has become popular in recent years especially for tackling problems for which more conventional computational approaches have proved ineffective. Problems of this type include pattern recognition, machine vision and motor control and these are precisely the types of problems that humans are normally very good at solving. This provides us with a strong impetus for turning to a biologically-inspired paradigm - that is, the artificial neural network. Perhaps the prime attraction of such artificial systems lies in the hope that they may share some of the remarkable processing capabilities of the human brain.

a. Origin of Neural Network. Research into neural networks stretches back as far as 1943. At that time, McCulloch and Pitts(18) were developing formulae to describe how neural networks could perform simple functions. In 1949, Hebb(15) contributed the "Hebb Rule" for adjusting connection strengths and this was followed by Rosenblatt(19) who developed the "perceptron algorithm", an early model for information storage and organization in the brain. Rosenblatt's work was controversial at the time and the field became unfashionable, leaving only a few workers who continued to work through the 1970's. Among these figures, the more influential ones have been Grossberg(14) and Kohonen(17). More recently increased interest has developed and among those who have contributed to the new resurgence in activity are Rumelhart and McClelland(20).

b. Learning in Neural Networks. The current spurt in research activity in neural networks is matched by a corresponding increase in research into learning algorithms. Essentially, neural networks can be trained by recognizing certain mappings from the inputs to the outputs. In general, each possible input (represented as a pattern of activity over the input units) is presented in turn and must elicit a certain pattern of activity in the output units of networks. Learning the required mapping

involves gradually tuning the set of connection weights by comparing the resulting output with the desired output and, in most cases this is an iterative procedure involving error minimization. One such learning mechanism is the "Back-Propagation Algorithm", advocated by Rumelhart and McClelland (20), and it is the approach adopted in our work on description of the learning methodology is now presented for the sake of completeness.

In the learning process, the network is presented with a pair of patterns corresponding to the input and the desired output. Using the existing weights, the network produces its own output pattern which is compared to the desired output pattern. The error at any output unit in layer  $k$  is given by:

$$e_k = t_k - o_k \quad (5.1)$$

where  $t_k$  is the desired (or "target") output for that unit in layer  $k$  and  $o_k$  is the actual output. An expression for the error function may be written as

$$E = \sum (t_k - o_k)^2 \quad (5.2)$$

Learning comprises changing the weights so as to minimize this error function in a gradient descent manner, the so-called "delta rule" for convergence towards optimum values for the weights may be stated in general as

$$\Delta w_{kj} = \eta \delta_k o_j \quad (5.3)$$

where the error signal  $\delta_k$  at an output unit  $k$  is given by

$$\delta_k = (t_k - o_k) o_k (1 - o_k) \quad (5.4)$$

and the error signal  $\delta_j$  for an arbitrarily hidden  $u_j$  is given by

$$\delta_j = o_j (1 - o_j) \sum \delta_k w_{kj} \quad (5.5)$$

in equation (5.3),  $\eta$  is termed the learning rate parameter and is one of a number of user-selected parameters which must be entered at the start of the machine learning process. The value can, of course, be changed during learning if this is deemed desirable (e.g. to speed the process up). An excellent account of this technique is found in the reference by its originators, Rumelhart and McClelland (20).

### 5.3 Applications of Neural Networks

We have presented a brief introduction to the subject of neural networks and we consider that such architectures can be applied to a number of different systems in the marine environment. Specifically, we are actively looking at three related areas namely:

- a) Fault detection
- b) Reconfigurable systems
- c) Multisensor integration/intelligent systems

In the first of these, pattern recognition methods have been in use for some time as a means of fault identification. We anticipate that the attractive features of the neural network may well overtake existing methods noting the success already reported by Sobajic and Pao(21) in applying neural network methods to fault analysis in electrical power systems.

The idea of reconfigurable controllers has been explored in the aviation industry and does have some scope within the marine field too (Fuzzard et al (13)). Jakubowicz(16) has discussed how neural networks can be effectively employed where the self-repair of damaged or faulty components is necessary. In particular, he proposes a neural architecture for implementing self-repairing sensor and identification systems onboard autonomous robotic vehicles operating in isolated environments (e.g. unmanned submersibles). The military advantages of such systems need no further exposition.

Interest has been growing in the use of multiple sensors to increase the capabilities of intelligent systems. For these systems to use multiple sensors effectively, methods are needed for integrating the sensor information into the operation of the system. Some typical applications that can benefit from the use of multiple sensors are military command and control systems, mobile robot navigation, multi target tracking and aircraft navigation. A feature common to these examples is the requirement that the system must intelligently interact with its environment without the complete control of human operator. Current research is showing that neural networks has a significant role to play in this area since they provide a fairly well established formalism with which to model the multisensor integration process. Neurons can be trained to represent sensory information and complex combinations of neurons can be activated in response to different sensory stimuli. A number of examples of these applications of neural networks may be found in Luo and Kay(23). In addition, considerable research has been directed to the development of appropriate representations for multisensor-based mobile robots operating in a remote environment. In the specific case of neural network studies, Jorgensen(24) has proposed dividing the environment into equal-sized volumetric cells and associating each with a neuron.

The magnitude of each neuron's activations corresponds to the probability that the cell it represents is occupied and the neurons are trained using sensory information. "Associative recall" can then be used to recognize objects and further processing can result in the discovery of optimal path for navigation.

#### 6. CONCLUDING REMARKS

Fault detection and restructurable control can be efficiently implemented on board of marine vehicles by means of relatively simple methods based on optimal linear filtering and control. Such methods, originally proposed and introduced in the aerospace field, are expected to result particularly useful in order to improve survivability and operation in a damage control environment. It seems, however, that their validity is limited to reduced complexity control, navigation and specific tasks.

An approach based on artificial neural networks methodology may be more adequate in the case of complex situations which cannot be described in terms of simplified linear mathematical models. The verification of such methodology should be carried out by using simulation techniques applied to specific marine systems.

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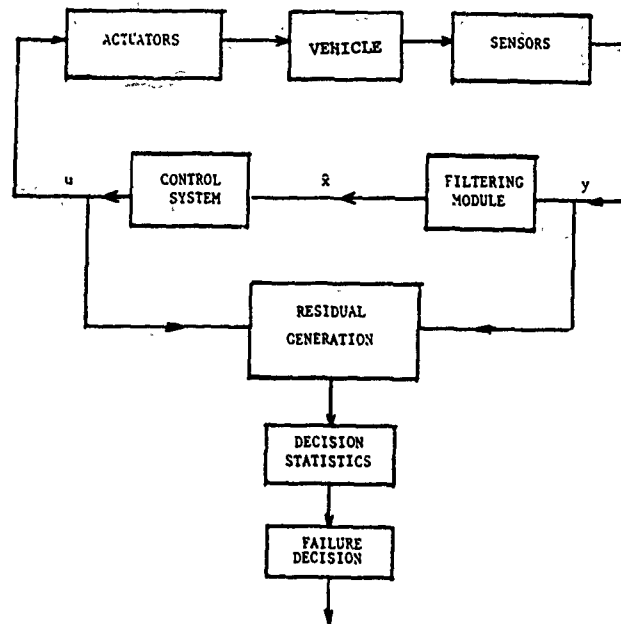


Fig. 1 Fault Detection and Identification Scheme

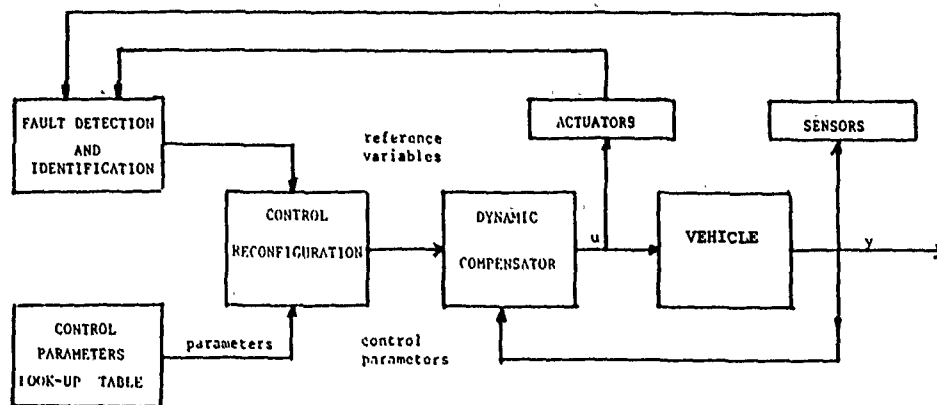


Fig. 2 FDI and Restructurable Control Scheme



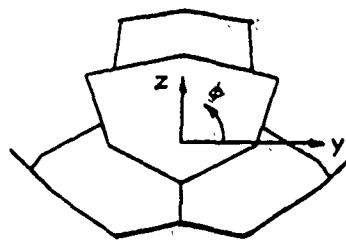
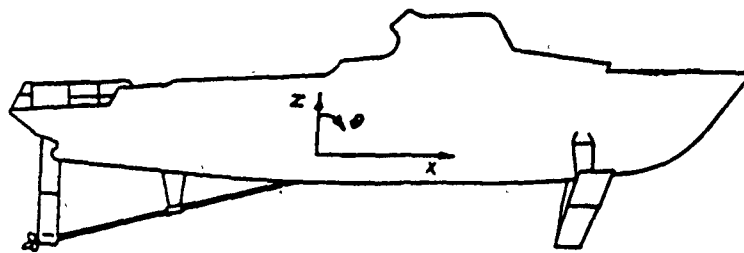


Fig. 3 Schematic representation of hydrofoil

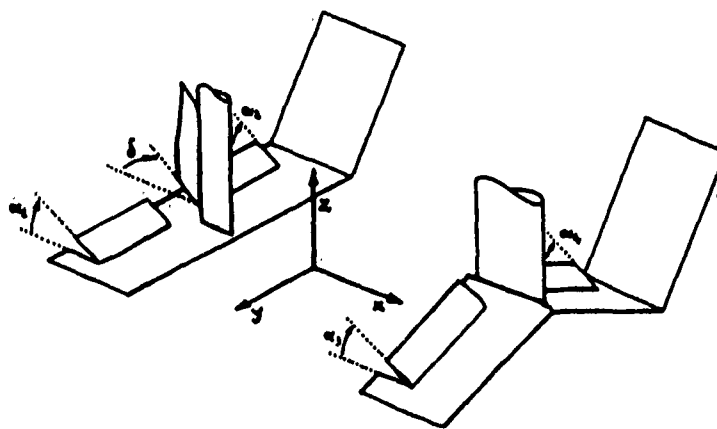


Fig. 4 General arrangement of control surfaces

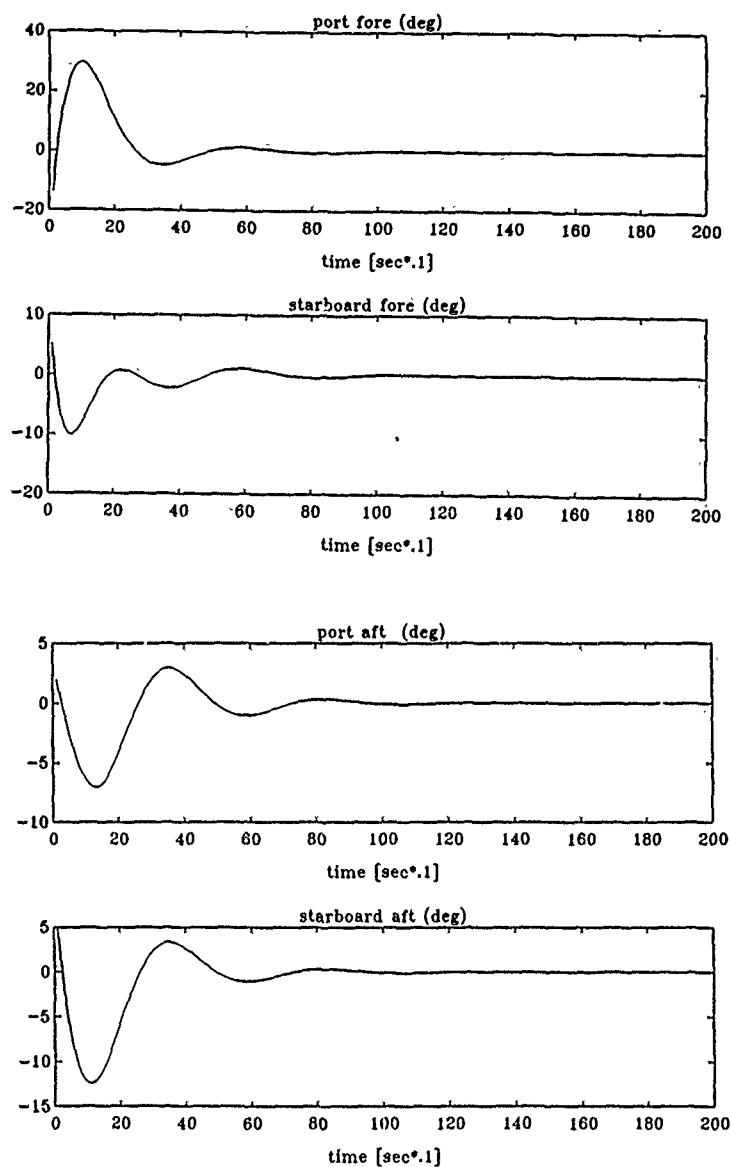


Fig. 5.1 Control surfaces time histories (normal operation)

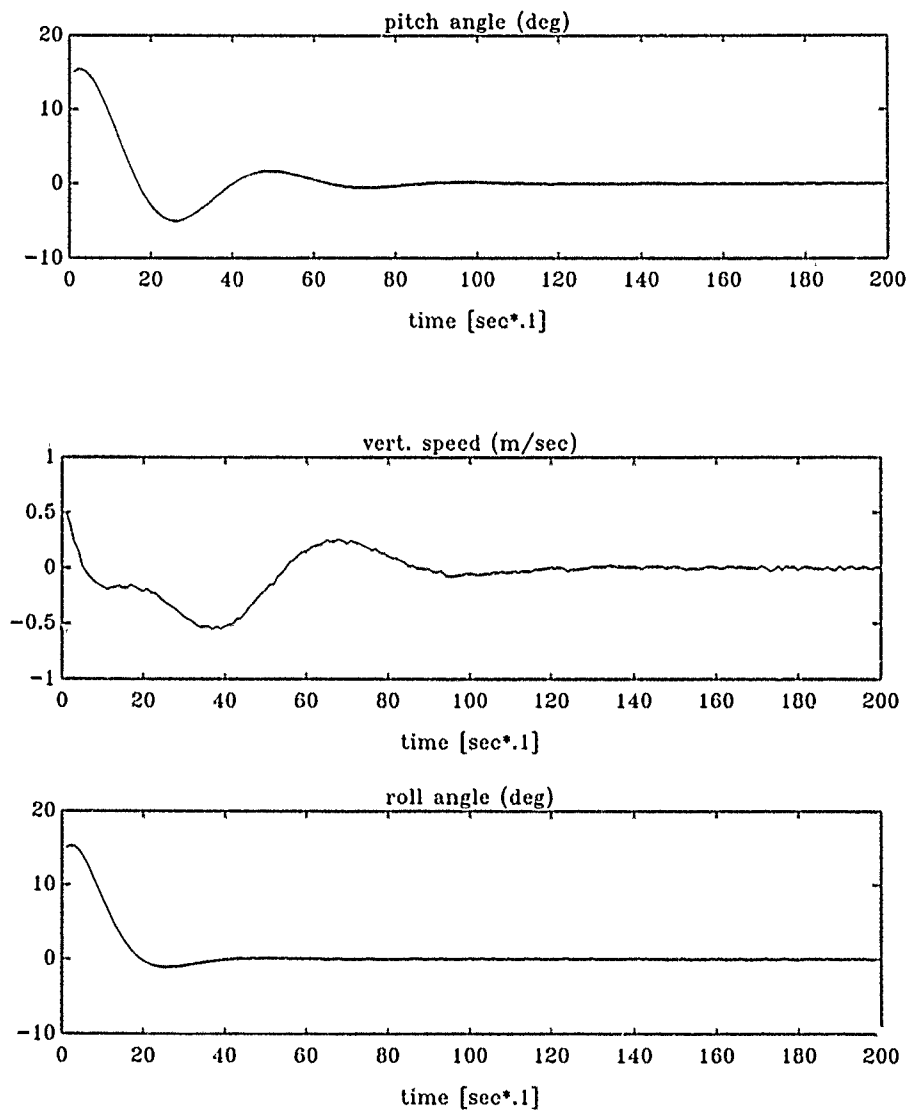


Fig. 5.2 Output variables time histories (normal operation)

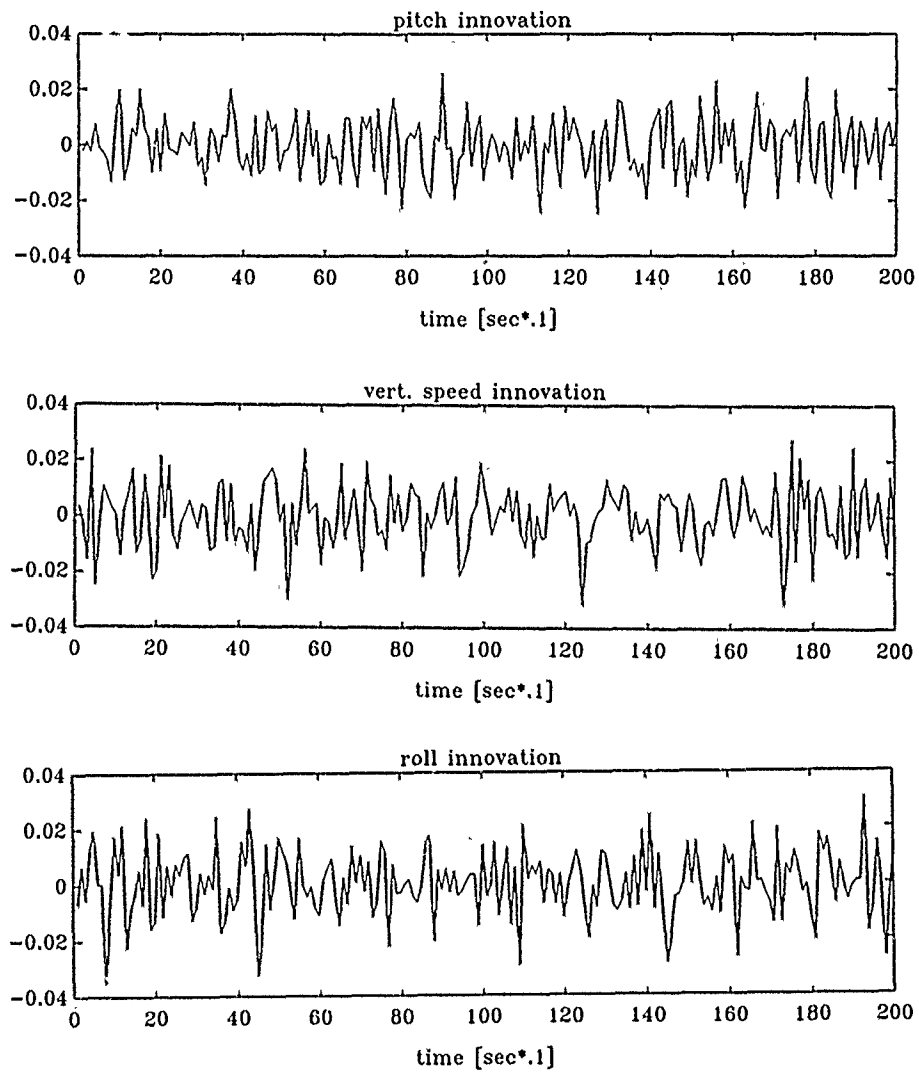


Fig. 5.3 Innovations variables time histories (normal operation)

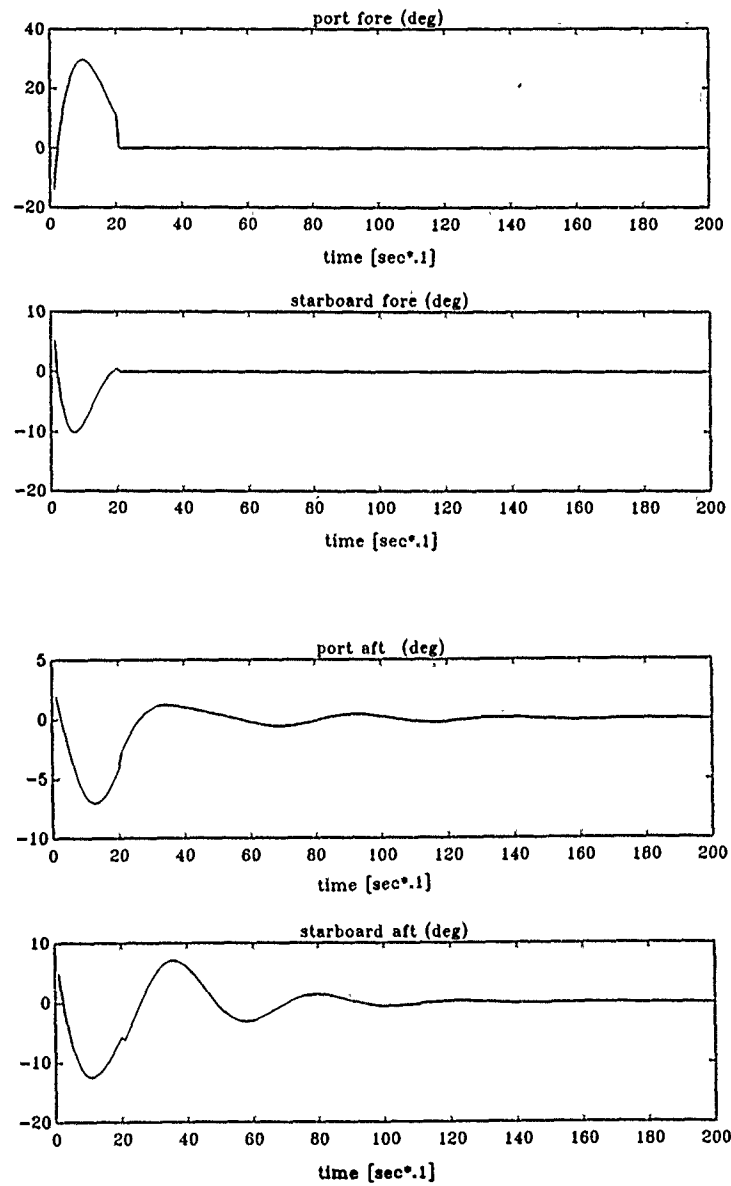


Fig. 6.1 Control surfaces time histories (fault recovery)

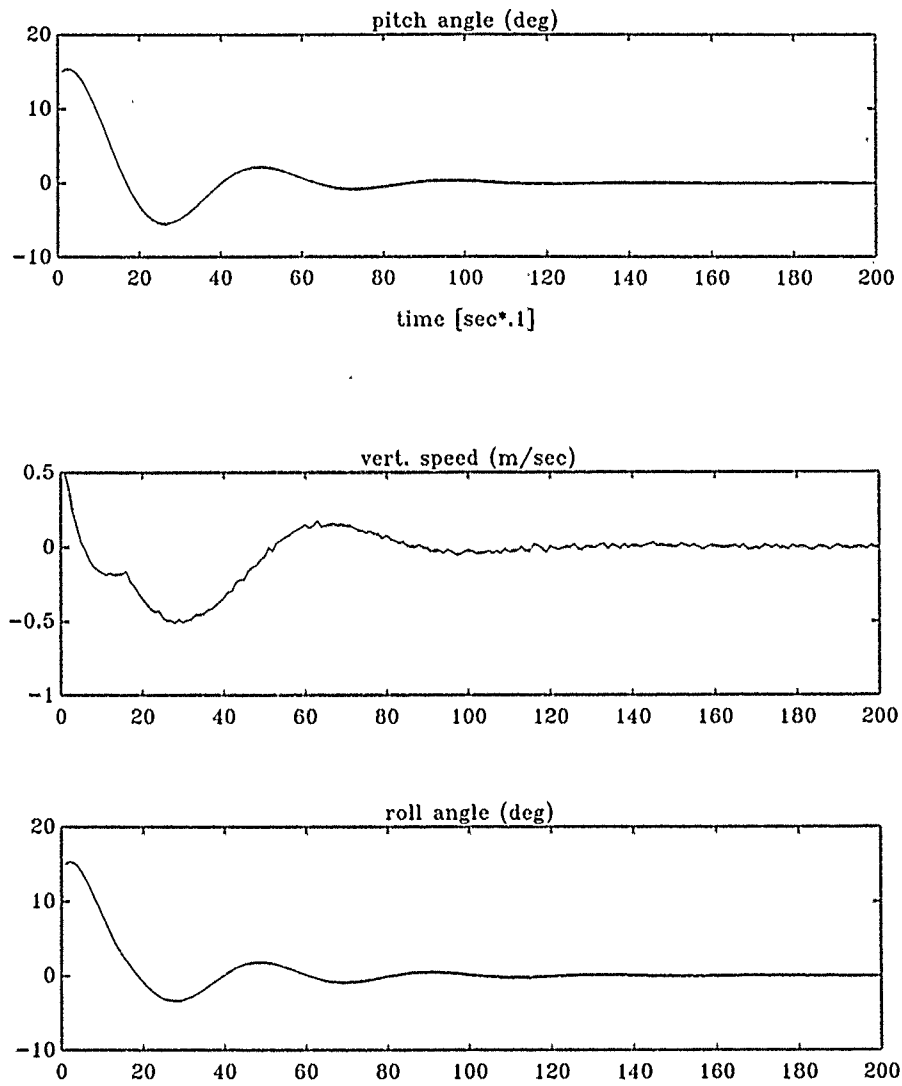


Fig. 6.2 Output variables time histories (fault recovery)

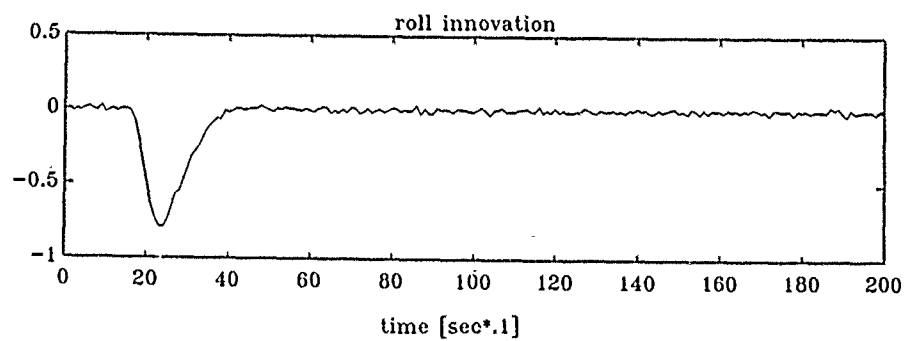
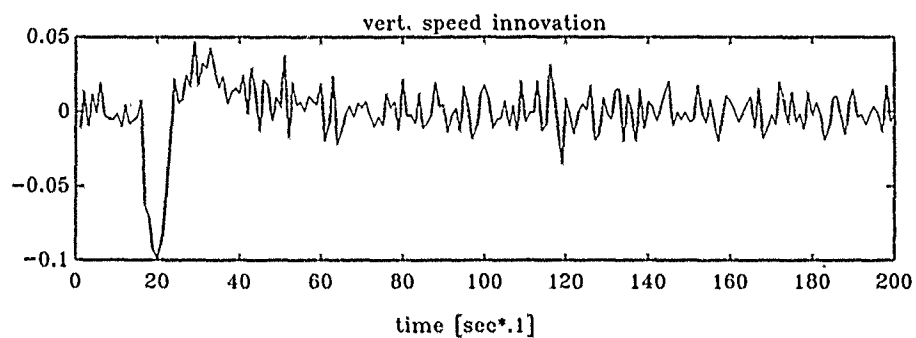
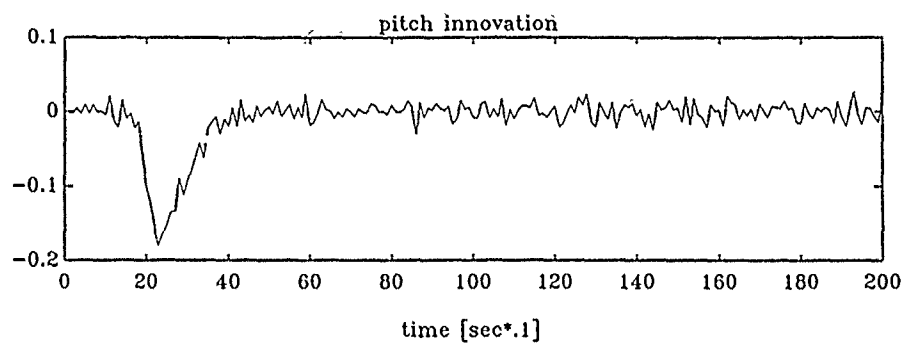


Fig. 6.3 Innovations variables time histories (fault recovery)

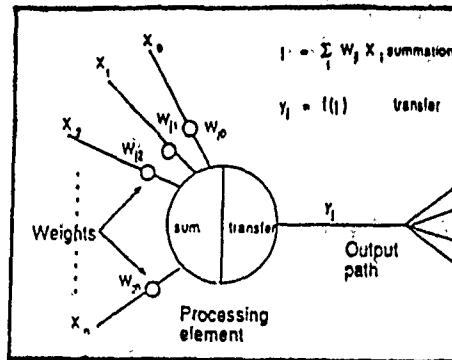


Fig. 7 Artificial Neuron Model

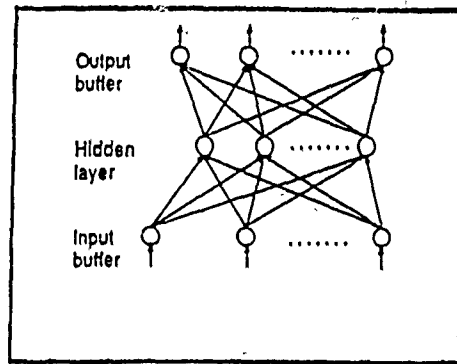


Fig. 8 General Network Topology

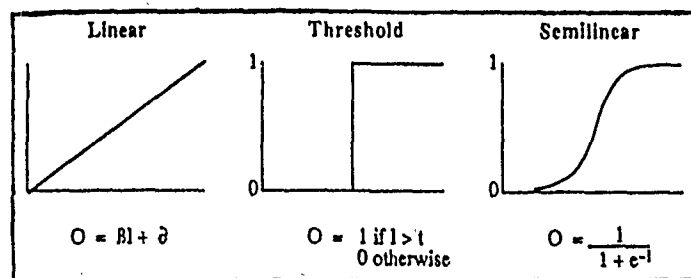


Fig. 9 Three Common Activation Functions



## SHIP CONTROL WITH ELECTRONIC CHART AND PATH PREDICTION

by Leo van Breda, Peter O. Passenier and Herke Schuffel  
TNO Institute for Perception, The Netherlands

### 1. ABSTRACT

Trends towards cost reduction will lead to single-handed bridge operation based on extensive automation. This expansion of automation converts the bridge to an operational centre for both navigational and supervisory tasks. This paper describes simulation experiments on using integrated electronic chart information and path prediction to improve ship control accuracy. Results show that the navigational performance using basic electronic chart information is at least equivalent to using conventional paper chart. A path predictor is especially effective when performing track keeping tasks with large course changes. The combination of electronic chart with path prediction will benefit navigational performance most effectively.

### 2. INTRODUCTION

Ship navigation is a hierarchically ordered process of control activities (1); a planning, monitoring and control level can be distinguished. At the highest level the master is planning the passage. This level mainly consists of decision making based upon information from different sources. At the intermediate level the mate is monitoring the manoeuvring process, judges deviations of the ship's path from the planned route and anticipates the ship's future path by observation of the surroundings and the ship's movements. At the lowest level the expected deviation between the ship's future path and the planned route are minimized by the helmsman. On these various levels automations can be applied to effectively replace the human operator, not only from the viewpoint that poor human operator capabilities should be eliminated, but also from the viewpoint that maximum alertness and involvement of the operator should be maintained (2). Table 1 shows a summary of a function allocation process for ship navigation for high workload conditions (3). At the planning level the master can use computers for optimizing the planned route with regard to for instance fuel consumption and travelling time. Automatic decision support systems are available though not fully tested yet. At the intermediate level information processing functions are supported by computers. For instance, ARPA systems perform routine tasks such as calculating collision avoidance, but for perception functions the human operator is still needed. At the control level an adaptive autopilot can replace the helmsman. Hence, for high workload

conditions the role of the navigator is that of look-out, decision maker and supervisor of automatic systems. Control functions are limited to set-point adjustments.

Table 1. Summary of a function allocation process for ship navigation during high workload conditions.

A = automated functions, M = manual functions.

activities	functions				
	perception		information	decision, processing motor control	
planning	A	M	A	M	M
monitoring	A	M	A		M
control		A	A		A

The ship handler, in the role of supervisor and decision maker, anticipates the deviation between the ship's future and planned position and orientation. The ship's future path is inferred from the perceived change of position and orientation (perceptual anticipation) and from knowledge of the ship's manoeuvring behaviour (cognitive anticipation) (4). For supporting the ship handler's and hence navigational performance effectively, three information layers in different colours are presented on an integrated navigation display in front of the ship handler. Planning information contains the geographical chart information, weather, waves and route information. Monitoring information presents ship's position and movement status such as heading, rate of turn, ground velocity of own ship and other vessels on the radar screen. Information on the control level shows rudder deflection and shaft revolutions.

This paper describes two experiments for determining the extend to which basic electronic chart information and path prediction support performance at the monitoring level.

The electronic chart (Electronic Chart Display and Information System, ECDIS) is presented on a graphic display and by applying suitable computer graphic techniques it is possible to combine chart and radar information on one screen (5). The integration of chart and radar information will enhance the navigational performance since separation between the conventional paper chart and the stand alone radar deteriorates such integration, given minimum acceptable chart details and resolution of the display. However, in both cases moderate to slight support to perceptual and cognitive anticipation is to be expected, since only the ground velocity vector can be used to extrapolate the change of ship's status.

A path predictor is a computer based system showing the ship's future path on a display. Human control of slow responding systems can be improved by means of predictive information (6, 7), however, applications of path prediction in the maritime field are hardly available, presumably for reasons of inadequate quality of prediction and deficiencies in proving operational advantages. It can be expected that in this case cognitive anticipation will be well supported, since the ship's future path is used to extrapolate the change of ship's status.

The path predictor used in this study was developed by the Delft University of Technology (8, 9) and designed for accurate application on board of ships. The design is based on a relatively simple mathematical model, the parameters of which are adapted to the changing conditions, instead of using a more complex non-linear model, which is difficult to adapt. A suitable method for on-line identification and adaptation of the prediction-model parameters and disturbances has been determined by a structural comparison of different, well-known, identification schemes. This has resulted in the application of Extended-Kalman filtering techniques to the identification and adaptation problem (see Appendix).

### 3. ELECTRONIC CHART

#### 3.1 Method

For determining the effectiveness of the electronic chart for the navigation task a simulator experiment was conducted. Eight subjects, watch-officers in active service, controlled a 40,000 DWT container vessel along twelve predetermined routes. During each trial suddenly an alternative route with a course change of 30, 45, 60 or 75 degrees was introduced in a random sequence. The time available for the subject to take action was at maximum 60 seconds. The scenario describing the other vessel traffic movements was such that continuous attention to the vessels' movements was needed. Deviations from the intended route were calculated as a root mean square error.

Two main conditions were investigated:

- (EC) Electronic Chart, showing basic electronic chart information in combination with ARPA radar on an integrated navigation display;
- (PC) Paper Chart, showing the conventional paper chart on a semi-automatic chart table in conjunction with the ARPA-information on a stand alone radar display.

On chart and radar the intended route was presented. On the radar display the own ship's heading, turn rate, speed and rudder deflection were indicated. The electronic chart met the specifications for the minimum configuration mentioned in the IHO standards (10, 11). The use of colours was conform the paper chart. The ARPA radar was true motion, true vector and north up (see Figure 1). In this condition the watch-officer could anticipate the ship's movement by extrapolation of the ground velocity vector. Together with the intended route and chart information there is a moderate condition for minimizing future errors.

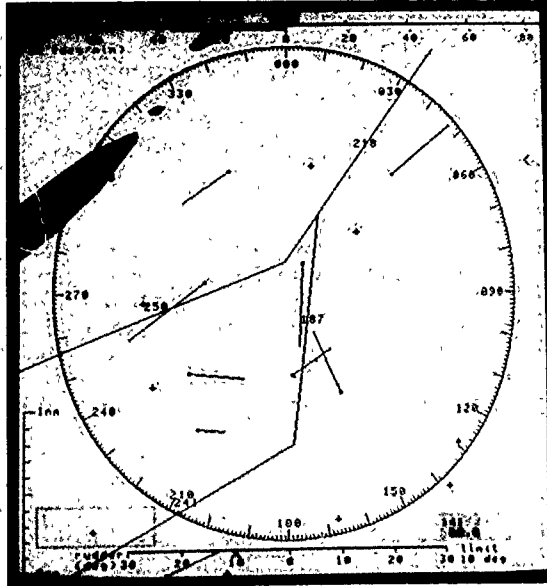


Figure 1. Electronic chart: radar and chart information presented on an integrated navigation display.



Figure 2. Paper chart placed on a semi-automatic chart table and a separate navigation display for radar information.

The conventional paper chart was placed on a semi-automatic chart table, directly at hand of the watch-officer. The own ship's position was indicated by a small light dot projected on the chart (see Figure 2). In this condition the watch-officer could anticipate the ship's movement by extrapolation of the ground velocity vector on the radar screen but he had to combine this information mentally with detailed information from the separate paper chart. This provides moderate condition for minimizing future track error.

### 3.2 Results

In Figure 3 the deviation from the intended route is shown, averaged over all subjects. As was expected in the paper chart condition, the deviation of the ship's path from the intended route is gradually increasing with larger course changes. Although not significant, in the electronic chart condition the deviation remains at a constant level of about 50 meters when performing limited course changes and joins the performance level of the paper chart condition for large course changes.

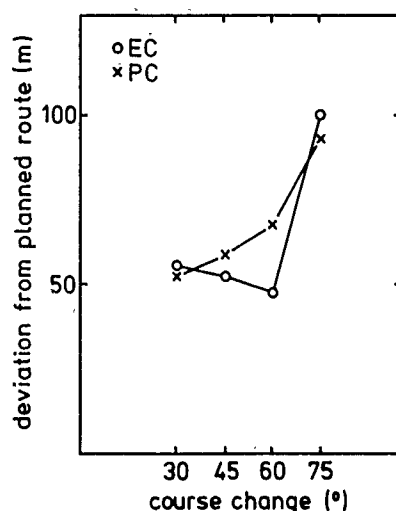


Figure 3. Deviation from the planned route for electronic chart and paper chart as a function of course change, averaged over subjects.

## 4. PATH PREDICTION

### 4.1 Method

For determining the navigational performance using the path predictor a second simulator experiment was conducted. Twelve subjects, being watch officers in active service, controlled a 40,000 DWT container vessel along six predetermined tracks. Each track consisted of five course changes (15, 30, 45,

75, 105 degrees) in random sequence. The intended route was shown on an integrated navigation display, depicting radar information, bearing and range marker, ship's heading, turn rate, speed and rudder reflection. Deviations from the intended route were determined by root mean square error calculations.

Three main conditions were investigated:

- (PP) Path Prediction, showing the ship's future path on the navigation display;
- (GV) Ground velocity Vector, showing the ship's true velocity vector;
- (PI) Parallel Indexing, showing the intended route.

With path prediction the intended route and the predicted path were continuously presented on the navigation display. The predicted track was a curved line that is being set by means of a trial manoeuvre. The watch-officer can fully anticipate the ship's path. In combination with the presented intended route, this provides an adequate way for minimizing the ship's future track error (see Figure 4).

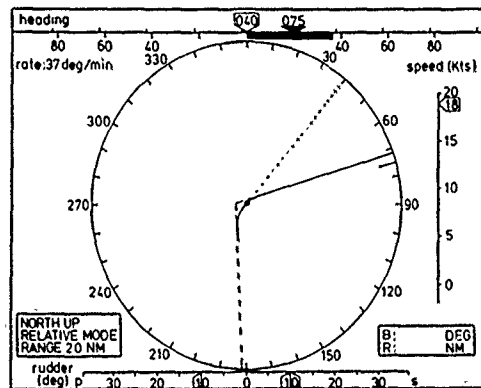


Figure 4. Path prediction, indicated by the solid line, with actual heading line and intended route.

With a ground velocity vector, the watch-officer can anticipate the ship's movements by extrapolation of the velocity vector. In combination with the intended route there is a moderate condition for minimizing the future track error (see Figure 5).

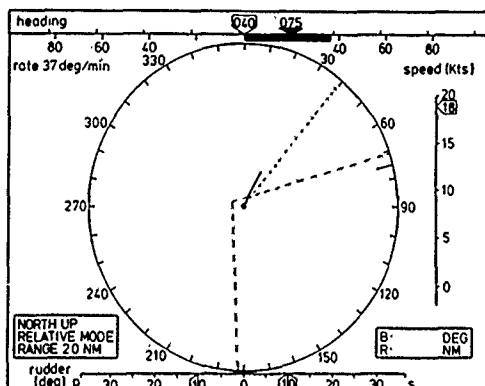


Figure 5. Ground velocity vector, indicated by the solid line, with heading line and intended route.

With parallel-indexing, principally the intended route is pursued. Compass, turn rate indicator and actual position provide minimal means to anticipate the ship's movement and future track error (see Figure 6).

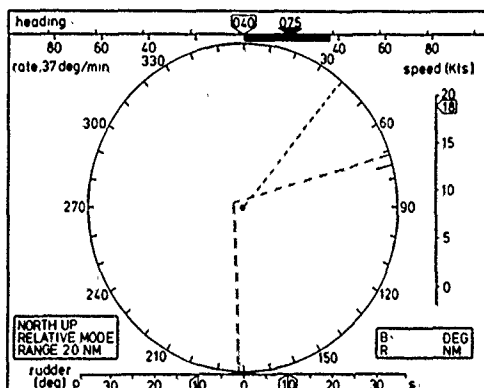


Figure 6. Parallel-indexing, for experimental purposes simplified to a pursuit tracking task, with a heading line and intended route.

#### 4.2 Results

In Figure 7 the deviation from the intended route for the conditions is shown, averaged over all subjects. The path prediction condition shows significant accurate performance ( $F = 65.6$ ;  $df = 2, 22$ ;  $p < 0.01$ ). The inaccuracy of manoeuvring with the ground velocity vector and the parallel-indexing method occurs when performing large course changes as was expected. Hence, path

prediction is effective, supporting particularly the ship handler's knowledge of the ship's behaviour. Anticipation by means of a ground velocity vector or by parallel-indexing is relatively less effective.

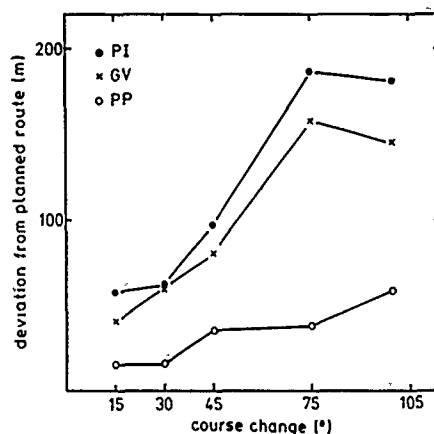


Figure 7. Deviation from the planned route as a function of information presentation and course change, averaged over subjects.

## 5. CONCLUSIONS

Results of the experiments show that the electronic chart is at least equivalent to the paper chart for the experimental conditions. The subjects were able to use the integrated electronic chart in unexpected situations as effective as radar with separate paper chart. In the electronic chart condition there is a tendency of improved navigational performance in situations with limited course changes. This is likely due to the integration of chart and radar information. However, when performing larger course changes anticipating behaviour is unsupported in both conditions and accuracy of the performance decreases both in the electronic and in the paper chart condition.

The use of a path predictor improves ship control accuracy considerably. Especially when performing track keeping tasks with large course changes there is a reduction in deviation from the intended route of about 70 percent. Path prediction supports cognitive anticipation.

For the optimal allocation of functions, it is suggested to combine the electronic chart with ARPA and path prediction.



## APPENDIX

The identification and adaptation problem consists of:

- on-line estimation of the prediction model state and parameters to calculate the predicted track;
- estimation of disturbances such as wind and current, to adapt the predicted track to these disturbances.

For this purpose a seven-dimensional Extended Kalman filter has been designed for the:

- filtering of the high-frequency wave motions;
- on-line estimation of the yaw-model parameters;
- estimation of the wind influence, which can be treated as an additional input to the yaw model.

The filter input consists of:  $(\delta, \hat{u})^T$ , with  $\delta$  the actual rudder angle and  $\hat{u}$  the estimated forward speed, provided by a separate filter.

The required measurements are:

$$z_y^T = (\tilde{r}, \tilde{\psi})$$

with  $\tilde{r}$  and  $\tilde{\psi}$  the wave-disturbed rate-of-turn and heading signals.

Besides this yaw filter, a six-dimensional Extended Kalman filter has been designed for the:

- filtering of the ship's observed position;
- filtering of the forward speed  $u$ ;
- estimation of the sway velocity  $v$ ;
- estimation of the current-speed vector  $\underline{u}_c$ .

The filter input consists of:  $(\hat{r}, \hat{\psi})^T$ , with  $\hat{r}$  the filtered rate of turn and  $\hat{\psi}$  the filtered heading, provided by the yaw filter.

The required measurements are:

$$z_p^T = (u_z, x_z, y_z)$$

with  $u_z$  the measured forward speed and  $x_z, y_z$  the observed position.

The main parameter of the filter is the variance of the position-fix measurement error, which is a characteristic of the positioning system.

The filtered forward speed is used by the yaw filter to normalize the estimated parameters of the yaw model according to:

$$\hat{K}^* = \hat{K} \cdot (L/\hat{u})$$

$$\hat{\tau}^* = \hat{\tau} \cdot (\hat{u}/L)$$

with  $K$  and  $\tau$  the yaw model gain and time constant and  $L$  the length of the ship.

The combination of the yaw filter and the position filter for the estimation of the prediction-model state and parameters is presented in Figure 8.

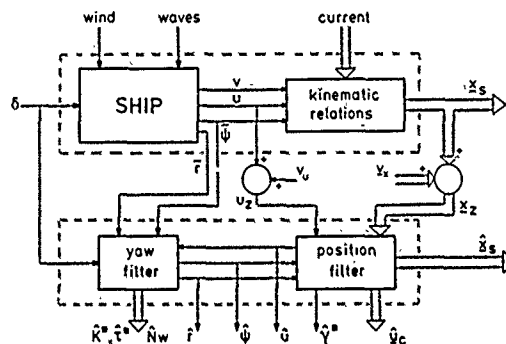


Figure 8. On-line state and parameter estimation.

In this figure  $\hat{x}_z$  is the ship's observed position with observation noise  $v_x$  and  $u_z$  is the measured forward speed with observation noise  $v_u$ .

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A Portable Automatic Control System for  
Ocean Research Operation of a Ship with  
a Controllable Pitch Propeller, a Rudder and a Bow Thruster

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ABSTRACT

The fisheries training ship " Oshoro Maru (1,400 G.T.) " is equipped with a controllable pitch propeller, a rudder, and a bow thruster. They are used in combination for both course keeping and speed control of the ship while conducting its ocean research operation.

While conducting ocean research operations, manually operating the ship via the actuators mentioned above, is troublesome due to strong external influences such as wind, waves and current. Adding to the problem is the limited number of actuators and so on. In order to solve these problems, a portable automatic ship control system for ship operation has been designed using computer simulations and full scale trial at sea.

The Portable Automatic Control System (PACS) consists of pre-programmed micro computer modules for control, operation, and I/O. This system makes it possible to directly select several combinations of actuators from console panels located the bridge deck and in the research room.

Results obtained so far, indicate this control system is able to reduce operator weariness more than the conventional manual cruise operations. This paper describes the implemented system with particular emphasis on the control system.

1. Introduction

Fisheries training ship " Oshoro Maru " of Hokkaido University is annually engaged in oceanographic and fisheries research

and also fisheries training cruises in the North and South Pacific Ocean. [1]

In the case of oceanographic research, CTD equipment and sounding machine are dropped over the ship's side by use of the very long cable (more than 3,000m). This is done so the crew can operate her well at dead slow speeds using the actuators of a Cpp, a rudder, and a bow thruster to keep her course and speed steady. This prevents measurement equipment from becoming damage due to cable tanglement under the ship.

However, manually operating these ship actuators is very troublesome against the external influences such as wind, waves and current. This situation is considerable mental and physical pressure to the operators. In order to solve these problems, we developed a portable automatic controller with particular emphases on keeping the ship's course and speed steady in dead slow speed or under stopping conditions against the external influences. The main design consideration is to keep both the ship and the instruments safe during ocean research operations.

An approach to achieve this control system and its designing information is described in Section 2. The computer simulation design and mathematical model are summarized in Section 3. The control system design is reviewed in Section 4. The results of full scale test and several problems occurred at full scale test are given in Section 5. Finally, in Section 6 it is concluded that the ship can be automatically controlled at smooth and medium sea condition, but in rough sea condition, it is necessary to adjust the control law and bow thruster for the endurance problems. It is also concluded that this automatic control system is safer than skilled manual control while course keeping at dead slow speeds or under stopping conditions.

## 2. Design Approach

### 2.1 Oceanographic Operation

" Oshoro Maru " is specially designed for fisheries training and oceanographic research. The ship is designed with a stern trawler equipped with a Cpp, a rudder, and a bow thruster. The particulars of the ship are summarized in Table 1. An outline of the ship's structure and the photograph are shown in Fig.1 and Photo.1. The maneuvering image during oceanographic observation, which may suggest basic strategies of the automatic control system, is shown in Fig. 2. At the stopping conditions, the long cable deploys the observation instrument over the port side of the midship near stern. [2]



Photo. 1 View of "Oshoro Maru"

Table 1 The particulars of "Oshoro Maru"

Length(oal)	72.85m	131 Tuna long line	
Length(pp)	66.00m	Hydraulic line hauler 0.2t × 272m/min	× 1 set
Breadth(mld)	12.60m	10 Salmon gill net	
Depth(mld)2nd Dk	3.40m	Hydraulic net hauler 0.3t × 177m/min	× 1 set
Upp Dk	5.20m	Oceanographic winch	
Full loaded draft	5.00m	01 Sounding machine	
Gross tonnage Japan/Int.	1383/1779t	Hydraulic 0.6t × 120m/min 4 φ × 3,000m	× 1 set
Call sign	JDNA	02 C.T.D. winch	
Main engine	Hanshin 6EL10 3,200ps × 210rpm × 1 set	Hydraulic 1t × 72m/min. 6.4 φ × 4,000m	× 1 set
Propeller	4-Bladed C.P.P. × 1 set	03 Underwater T.V. winch	
Main generator	450KVA × 3 sets	Electric 0.5t × 2-12m/min 20 φ × 500m	× 1 set
Bow thruster	Thrust 5.5t, 390KW × 1 set	04 Sampling winch	
Anti rolling tank	U duct type × 1 set	Hydraulic 2.5t × 120m/min. 12 φ × 3,200m	× 1 set
Trial max. speed	14.4knots	Laboratory	
Service speed(85% load)	13.4knots	Computer, Disk, Graphic plotter, Printer,	
Number of complement	Officers 13p. Crews 27p. Scientists 6p. Cadets 60p. Total 106p	Aquarium for culture fishes. Thermo salinometer	
Fishing gear		Fishing equipment	
01 Trawl winch		Sonar, Fish finder, Net recorder, Quantitative echo sounding system, Otter trawl data logging and analyzing system	
Hydraulic 10t × 80m/min. 22 φ 3000m	× 1 set	Navigation equipment	
02 Net carrier		Gyro compass, Radar × 2. Anti collision system.	
Hydraulic 0.3t × 100m/min	× 2 sets	Hybrid navigation system (Loran A & C, Omega, N.N.S.S. Decca processor), Decca, Electro magnetic log, Ultrasonic anemometer	

To prevent the cable from tangling under the ship or into the screw propeller during the observation, the ship was controlled as described below:

\* Get the wind on the port side of the ship about 10 deg. ahead.

\* Set the ship in hovering position or with only a small movement astern.

In this manner, if the ship is off its desired performance, then her course and speed would be adjusted by a Cpp and a rudder. However, if this does not produce sufficient results then the bow thruster can be employed in cooperation with a Cpp and a rudder without chattering action.

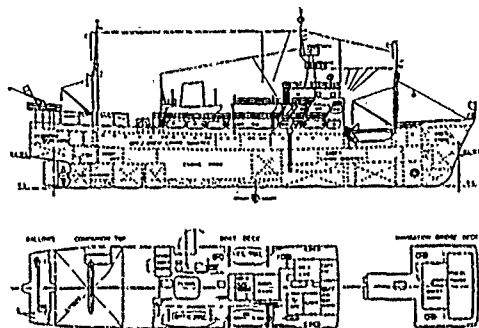


Fig. 1 An outline of "Oshoro Maru"

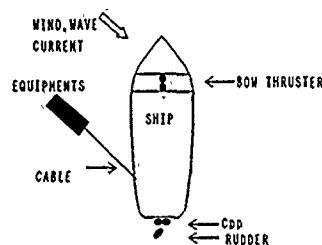


Fig. 2 Oceanographic operation

## 2.2 Control Dynamics

The basic problem for the realization of a controller is how to obtain practical information useful to the object system. One of the methods is the statistical approach which makes use of a parametric model that is obtained by the data analysis. The design is based on the understanding of the system behavior which is obtained by careful statistical analysis of the actual data. By using an appropriate statistical model, this approach provides a model that takes into account both characteristics of the system and noise sources. The detail of this method is discussed by the authors. [3][4]

Here we introduce the analysis of numerical data observed by an actual experiment at sea. Fig.3 shows a portion of head angle, rudder angle and pitch angle of thruster. Fig.4 shows the decomposition of power of yaw angle, rudder angle, and pitch angle of bow thruster in relation scale. Fig.5 shows the relative power contribution of system variables. These figures show that the contribution from rudder and bow thruster are significant in the low frequency band.

These results show the effects of some definite feedback relations occurring within the controlled variables. These are significantly amplifying the frequency components mentioned above within the random sea. [5]

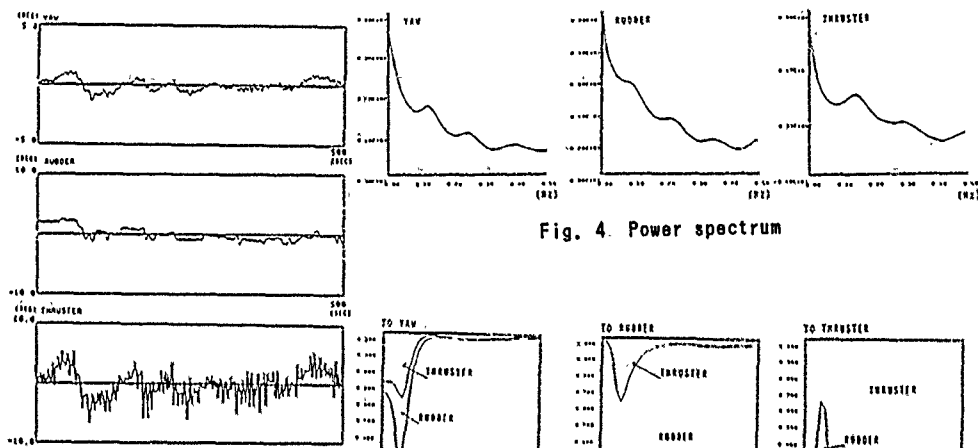


Fig. 3 Observed data  
( Actual Sea Test )

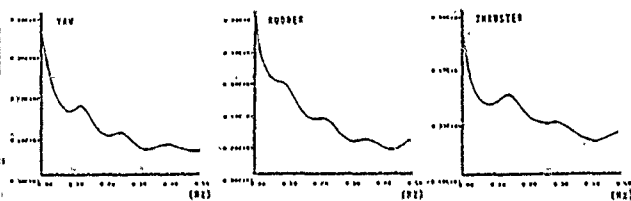


Fig. 4 Power spectrum

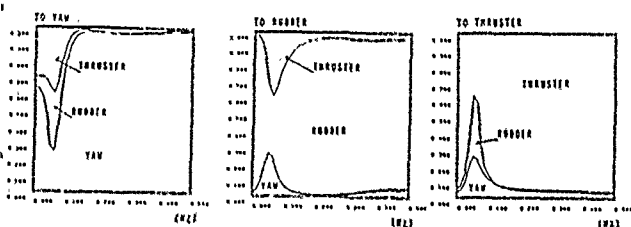


Fig. 5 Relative power contribution

### 2.3 Design Concepts

In aid of the understanding for the configuration of the proposed Portable Automatic Control System (PACS), a brief description of each concept is given below:

- \* The PACS introduces a step forward control of the shipboard, by combining the reliability and flexibility of digital computers with the simplicity of control procedures.

- \* The manual control of actuators mentioned above, leads to complex operation adjustment. The PACS may greatly decrease this troublesome job.

- \* The PACS is able to select the mode of the manual control or the automatic control for each actuators, and in the automatic control mode, to select combinations of actuators separately depending on sea conditions.

- \* The PACS is able to set in suitable position on board, for example steering room in the bridge deck, wing deck or research room.

### 3. Portable Automatic Control System

#### 3.1 Function and Operating

The organization of PACS as a whole, is represented by Fig.6. The PACS can select the control mode of manual or automatic in a bow thruster, a Cpp and a rudder, respectively as shown in Fig.7. The desired direction is controlled with a bow thruster and a rudder depending on the Cpp movement. Also the desired velocity is controlled with only a Cpp.

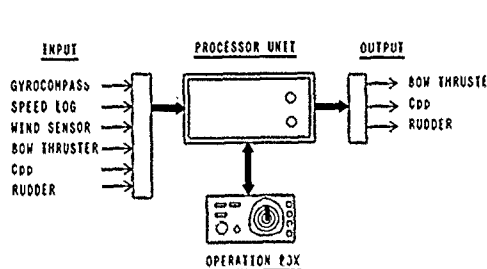


Fig. 6 Organization of PACS

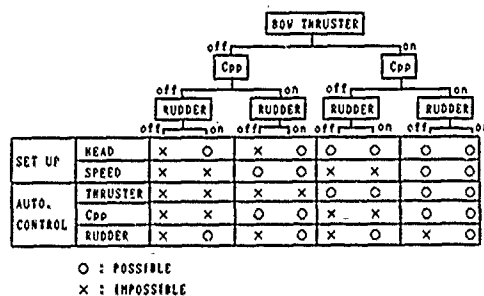


Fig. 7 Control mode

We show specific control modes below:

#### \* Full Automatic Control

In this case, a bow thruster, a Cpp, and a rudder are selected in auto mode. A desired velocity and heading angle of the ship is set with the dial on the operator's panel. A pitch angle of the bow thruster, Cpp, and rudder angle are calculated by the main computers in the control console so as to keep her velocity and heading angle. This is based on the signal from the doppler log and gyro compass. The desired direction are controlled with a bow thruster and a rudder dependent on a Cpp movement, and the desired velocity is controlled with only a Cpp.

#### \* Manual Control

In this case, a bow thruster, a Cpp, and a rudder are selected by manual mode. The pitch angle of bow thruster and Cpp are selected in proportion to the inclination angle of the joystick. The rudder angle is ordered by the indication angle of the dial. In this mode the crew operates the ship with the joystick lever and the rudder dial.



#### \* Semi-Automatic Control

In this case, a bow thruster, a Cpp, and a rudder are respectively selected by manual or auto mode. For instance, when a bow thruster is selected in auto mode, and besides a Cpp and a rudder in manual mode, a desired direction may be set on the operator's panel. Then a pitch angle of bow thruster is calculated by the computers so as to keep the direction. Furthermore, a Cpp and a rudder may be controlled with a joystick and dial freely.

The control sequences mentioned above are shown in Fig.8.

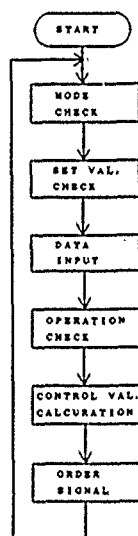


Fig. 8 Control sequences

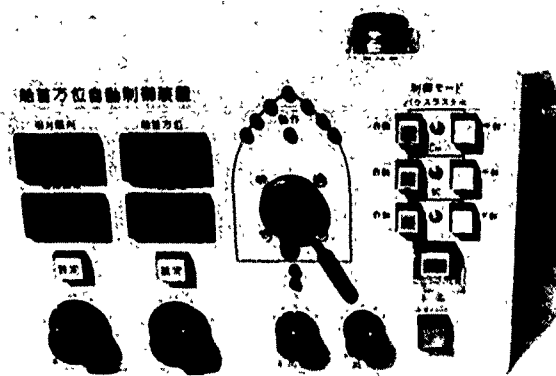


Photo. 2 Portable operation box

### 3.2 System Configuration

#### \* Hardware

PACS consists of two components; one is a processor unit with a 16-bit CPU, and the other is a portable control unit with a joystick and dial. Photo 2 shows the appearance of the portable operation box with its joystick, dial and several buttons and display units. A single on-board computer(MAC6000) and the appearance of the processor unit are, shown in Photo.3. A special feature is the button switches located on the right side of the joystick which enables easy mode change.

Once the mode is changed, the ship's heading and speed can be controlled by selecting the combination mode. This can set each actuators on this operator's panel in automatic or manual mode. An operator's panel and its faculties are illustrated in Fig.9. The ship is already equipped with a manual operation apparatus on the operation console in the bridge. PACS was installed by setting the CPU control circuit as shown in Fig.10, and by using the original control apparatus as much as possible.

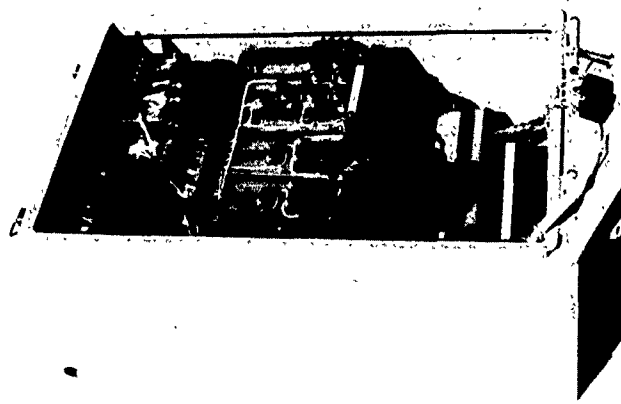


Photo. 3 Processor unit

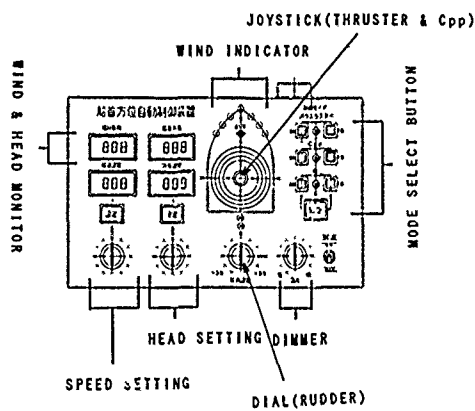


Fig. 9 Operation panel

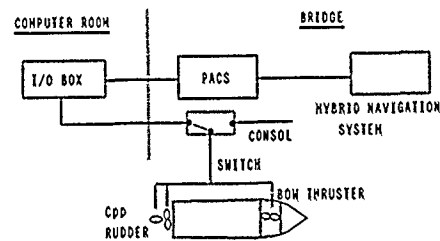


Fig. 10 Ship control system

It was judged very important that all in/outgoing signals are correctly insulated and isolated one from another. For this reason, every input/output signal coming from, or going into, the PACS is processed according to the scheme of Fig.11.

\* Software

The implementation of the software design was made bearing in mind the follows:

- 1) an ability to deal with large program size, quick software analysis, design, writing and debugging, minimizing at faults during real operation.
- 2) possibility to model the software easily during sea trials.

For these purposes the application development on the MAC6000 was done in a greatly simplified manner by using high-level languages and functions. Development aids were prepared and run-time communication support was conducted.

The MAC6000 control program for the PACS is divided into four parts, and constructed with the following functions:

- \* Disposition of extreme values
- \* Filtering of input data
- \* Modified multi variate PID control
- \* Wind compensation
- \* Distribution of calculated power to several actuator
- \* Management of abnormal movement of several actuator
- \* Monitor and printing functions.

The force allocation sequences are as follows:

The total forces and moment which are required from the regulators, must be converted to controller, rudder, and Cpp commands. This is done in the force allocation algorithm with and without the use of a bow thruster. The latter mode is used for the ship operation requiring less vibration and noise reduction. In this mode the controller commands to a Cpp and a rudder are computed to give force and moment balance. The bow thruster is used for operating at low speed and for hovering.

In this force allocation mode, the controller commands to the Cpp are not only determined for an axis force, but also for the rudder turning moment. If, however, it is not possible to obtain a sufficient moment, the bow thruster is also controlled together with the rudder. The commands to the rudder are ordered, if the Cpp is going to a positive pitch, even though the corresponding rudder command is always zero if negative pitch.

Details of the program structure control is presented in Fig.12.

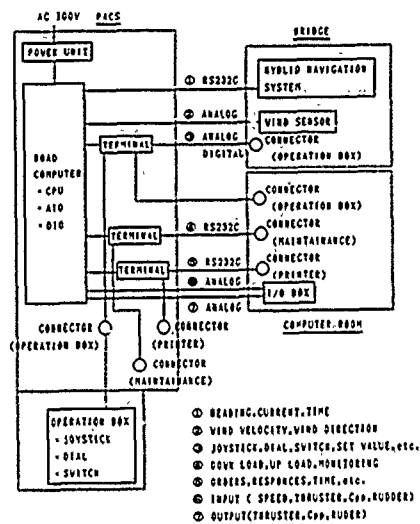


Fig. 11 Schematic diagram of signal line

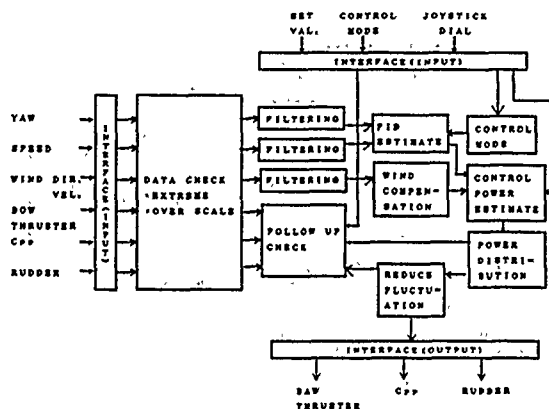


Fig. 12 Structure of control program

#### 4. Simulation Study

##### 4.1 Simulation System

Since the ship was not yet built, and the control program was being studied, the only practical way to implement the control algorithm was to use the simulator technique. For this simulation, the main hydrodynamic and aerodynamic data were obtained from model ship basin test and from wind tunnel test. The Planner Motion Mechanism (PMM) test, which is a kind of forced oscillation test, was carried out about the scaled model ship of the "Oshoro Maru" at Akishima Laboratories (Mitsui Zosen) Inc. as shown in Photo.4.

The total simulation was carried out on a desktop ship handling simulator (Called Harbor Master). The simulator communicated with a PACS substitute via a serial (RS232C) data link. The block diagram of this simulator system is shown in Fig.13. [6]

## 4.2 Ship Dynamics

A mathematical model of three principal equations, describing longitudinal and lateral and yaw motion, was developed for the simulations and the control system design. The variables used to describe the horizontal ship motions are explained in Fig.14.

The principal equations are expressed as follows:

$$m(u - vr) = XH + XE$$

$$m(v + ur) = YH + YE$$

$$I_{zz}r = NH + NE$$

The hydrodynamic forces  $XH$ ,  $YH$ , and moment  $NH$  are complicated functions of ship motion, rudder angle, and propeller thrust. The external influences  $XE$ ,  $YE$ , and  $NE$  are complicated function of wind, wave, and current forces. [7]

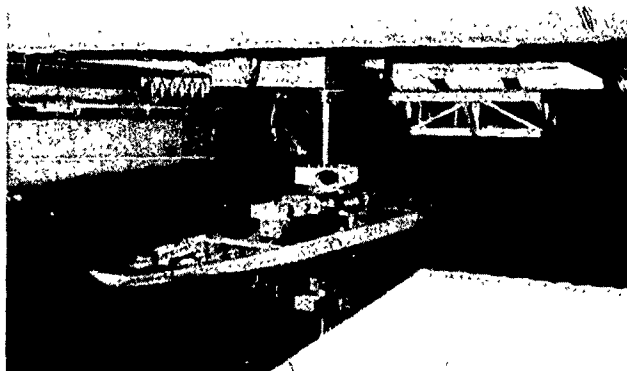


Photo. 4 View of PMM test

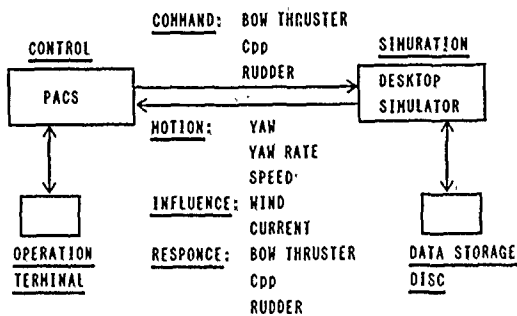


Fig. 13 Block diagram of simulation system

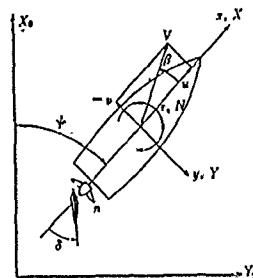


Fig. 14 Coordinate system

### 4.3 Simulation Results

Before implementing the PACS to an actual ship, we tried a control simulation. The main purpose of these simulations were to examine the control algorithm and gain constants for the PACS.

Fig.15 and Fig.16 show the course and velocity stability performances of the PACS in terms of trajectory, time history of heading, velocity and several actuators. Through these control simulations, the control algorithm and gain constants were reasonably planned. The circumstances during the simulations are shown in Table 2.

## 5. Full Scale Test

### 5.1 Test's Results

The PACS is currently operating the "Oshoro Maru". It is installed as a part of an integrated system. Fig.17 shows the result of the PACS operating the ship in light sea condition. These were carried out under relative condition wind speed averagely 10 (m/s) and the direction of about port 10 (deg.) bow. This figure shows the ship's velocity and course deviation. We can see that velocity and course keeping quality is stabilizing.

Fig.18 shows typical result from the sea tests in a fresh breeze state. This test was carried out under the wind condition of relative speed until speed 10 (m/s) averagely and the direction of port 10 (deg.) bow was obtained. These were wide fluctuation in direction. In this case, the course keeping performance was becoming wrong.

These results suggest that if fluctuations of wind direction are wide, the control sequence of the bow thruster can't satisfy the course keeping performance.

Table 2 Circumstance of simulation

DESIRED VALUE		INFLUENCE			
		WIND(from)		CURRENT(to)	
HEAD(deg)	SPEED(kts)	vel.(m/s)	dir.(deg)	vel.(kts)	dir.(deg)
0.0	0.0	10.0	350.0	0.0	0.0
350.0	0.5	10.0	340.0	1.0	170.0

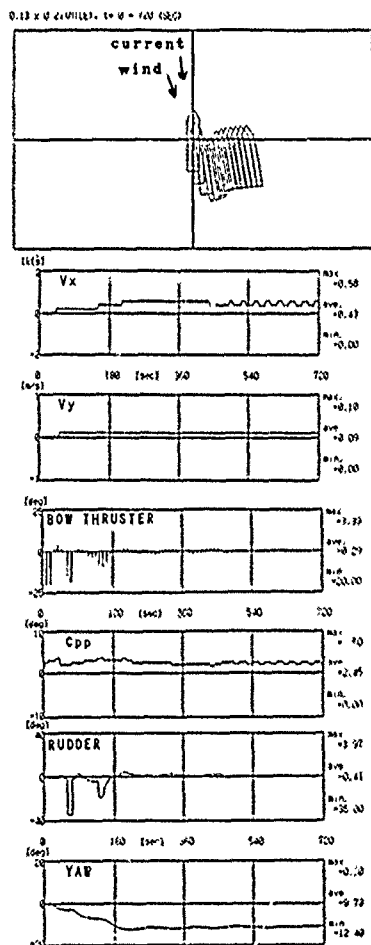


Fig. 15 Simulation result  
(under wind & current)

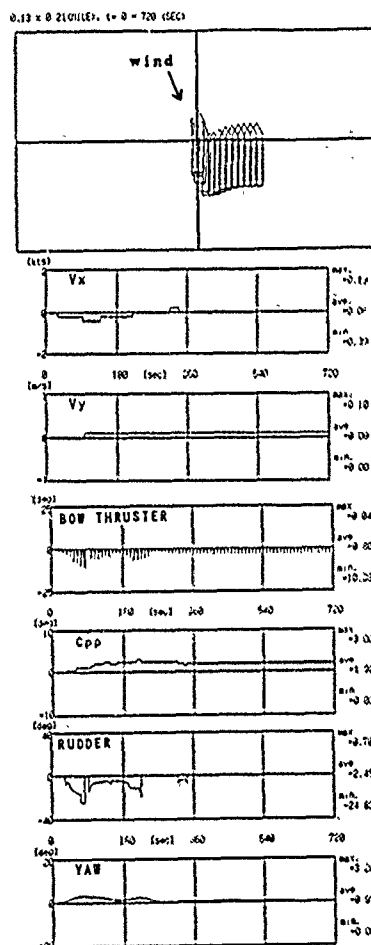


Fig. 16 Simulation result  
(under wind)

## 5.2 Problems

The full scale tests carried out on PACS, indicate that a PID controller would be very difficult to implement with sufficient security over the entire range of operations for the "Oshoro Maru".

The reason for this lie in several characteristics as described below:

\* It is clear that the pressure system of the bow thruster of "Oshoro Maru" is not preliminary designed for continuous driving.

\* Conventional PID control predominantly deals with linear systems within moderate disturbances.

However, this control approach will not always be satisfactory when the operating conditions change. The actuators of a bow thruster, a Cpp and a rudder have the requests of the operation with a nonlinear characteristics. These create difficulties unless special precautions are taken.

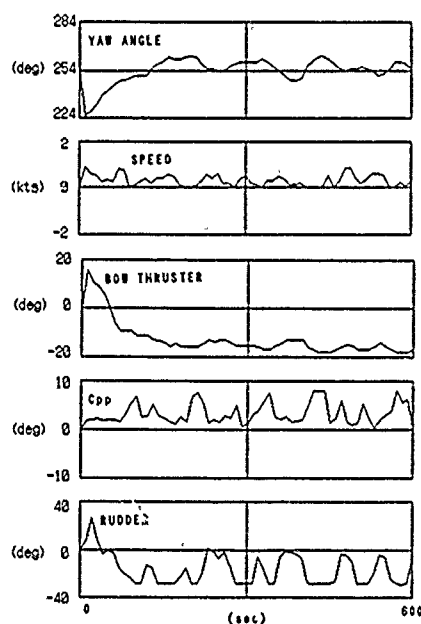


Fig. 17 Full scale result( light sea )  
(set course & speed 255 deg., 0.5 kts)

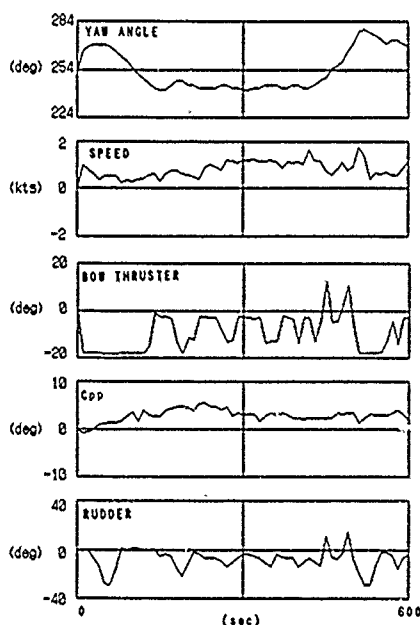


Fig. 18 Full scale result(breeze sea)  
(set course & speed 255 deg., 1.0 kts)



## 6. Conclusions

The PACS for oceanographic maneuvering of the "Oshoro Maru" was designed. The performance of the PACS was investigated by simulating studies and actual sea tests. The PACS has the following features:

- \* The PACS can operate the ship and the actuators under manual, semi-auto, and full automatic control by mean of actuator selection buttons.

- \* The PACS can control the ship's heading and speed automatically in the automatic mode.

- \* Joystick and dial control can adjust the ship's velocity and direction.

- \* The PACS is operated away from the control console.

- \* The PACS has high reliability with the adoption of a board computer and a ROM in the processor unit.

- \* Based on the owner's specification of the ship, as well as the condition of the sea in the area where the vessel is to operate, the control situation is simulated to help in the design and operation of the PACS.

It is concluded that the ship can be automatically operated at wind speeds not exceeding approximate 10 (m/s) and when wind direction is almost steady. For wide fluctuations of wind direction, it is necessary to modified the control sequence in consideration of the pressure system of bow thruster. Now we are going to describe simple robust methods that can be used to get crude estimates of automatic control system.

## 7. Acknowledgments

The authors are grateful to the crew of the "Oshoro Maru" for their help in implementing the PACS and their support in the actual sea tests.

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## ON THE MANEUVERING QUALITIES OF SHIPS

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### 1. ABSTRACT

This paper presents a preliminary study of a new index for measuring the maneuverability of ships. The index is a ratio that depends on hull parameters and compares transient changes in sway to variations in yaw-rate. The index discriminates between hulls on the basis of whether or not they give rise to a significant change in sway due to a unit deviation in rate of turn.

### 2. INTRODUCTION

The ability to change or maintain direction and speed is an essential feature of safe and efficient ships. In order to assess or predict handling quality one must be able to relate the vessel's motion to its active and passive controls. Quantitative measures of ship behavior during steady maneuvers are widely used in the analysis of stability and control [1,2]. These indices are defined by linear hydrodynamic coefficients and in principle can be evaluated without resorting to either sea trials or digital simulations. They provide a quick and accurate means of relating general performance to ship parameters. However, shiphandlers are often more interested in the transient effects of small course corrections than in the steady characteristics of a vessel [3]. The assessment of nonsteady behavior, in contrast to that of steady behavior, requires full-scale trials, captive model tests or expensive numerical computations.

A new measure of maneuverability is presented in this article. The index can be employed to measure ship performance during either steady or transient motion and can be evaluated without elaborate trials or calculations. For a given drift angle and rate of turn the index discriminates between hulls on the basis of whether or not they support a large change in sway in response to a small transient variation in yaw-rate. The index is developed for the standard set of surge-sway-yaw equations describing the motion of a surface ship. The dynamical system,

index and its computation are discussed briefly in the next section. A more complete development will be presented elsewhere.

The behavior of the index with respect to the dynamic variables surge speed, sway speed and yaw-rate is presented in section 4. This behavior is related to the maneuvering quality of five hulls. Each hull is associated with a particular category of vessel: tanker, cargo, mariner type, ferryboat and whale ship. Graphical evidence indicates that overall performance improves by reducing the value of the index. The deviation of the index with respect to the hull parameters is discussed in section 5. Variations of the geometric characteristics of a mariner type hull are studied as representative examples. Application of the index to ship design and the development of maneuvering criteria is discussed in the conclusion.

### 3. MANEUVERABILITY INDEX

The equations of motion for a surface ship in calm water are:

$$\begin{aligned}(m+m_x)\dot{u} - (m+m_y)vr &= X(u, v, r) & (\text{surge}) \\ (m+m_y)\dot{v} + (m+m_x)ur &= Y(u, v, r) & (\text{sway}) \\ (I_{zz} + J_{zz})\dot{r} &= N(u, v, r) & (\text{yaw})\end{aligned}\tag{2.1}$$

see [2,4,6]. Here  $u$  is the ship forward velocity (surge speed)  $v$  is the lateral velocity (sway speed) and  $r$  is the rotational yaw-rate. The dot notation is used to indicate a time derivative. The terms on the left-hand side of (2.1) contain the inertial and added mass terms. The expressions on the right-hand side represent hydrodynamic and external forces and moments acting on the ship. Their dependence on  $u$ ,  $v$ , and  $r$  is explicitly indicated in (2.1). In this work  $X$ ,  $Y$ , and  $N$  represent the force-moment system of a bare symmetric hull. Once appropriate initial conditions are specified, system (2.1) defines the hull's path by describing the evolution of  $u(t)$ ,  $v(t)$  and  $r(t)$  with respect to time.

As the hull moves, sway varies relative to the yaw-rate and the rate of that change

$$Q = dv/dr \tag{2.2}$$

is a measure of the hull's maneuverability. The identity  $dv/dr = \dot{v}/\dot{r}$  implies that  $Q$  is smaller for hulls that maneuver at a high rate of yaw speed without giving rise to significant change in lateral

velocity than for hulls that support a high rate of sway speed and a small variation in yaw-rate.

Expression (2.2) is evaluated on a trajectory of (2.1) and is a function of hull parameters and the dynamic variables  $u, v$  and  $r$ . It follows from  $dv/dr = \dot{v}/\dot{r}$  and the sway-yaw components of (2.1) that

$$Q(u, v, r) = \{ (I_{zz} + J_{zz}) / (m + m_y) \} \{ (Y(u, v, r) - (m + m_x)ur) / N(u, v, r) \} \quad (2.3)$$

is an algebraic ratio provided  $(u, v, r)$  is a transient trajectory. For a steady maneuver, (2.3) is indeterminate and a limiting process must be employed to evaluate  $Q$ . This calculation will be discussed in a subsequent publication.

In order to employ  $Q$  as an index of hull performance, it is necessary to evaluate (2.3) accurately for a wide range of hull parameters. This can be achieved by expressing  $Y, N, I, m, m_x, m_y$  in terms of hydrodynamic coefficients obtained by theoretical and semiempirical means, [5]. For purposes of comparison it is also convenient to render (2.3) nondimensional. The dimensional unit of (2.3) is length; therefore

$$Q' = Q/L \quad (2.4)$$

is a nondimensional index, where  $L$  is the hull's length.

TABLE 1

	L	B	T	cb
TANKER	216	30.6	10.3	0.81
CARGO	75	11.9	4.8	0.74
MARINER	160	23.4	7.6	0.58
FERRYBOAT	113	15.9	6.8	0.56
WHALER	57	9.5	3.5	0.46

(L, B and T in meters)

#### 4. VARIATION OF MANEUVERING QUALITIES WITH RESPECT TO DYNAMIC VARIABLES

The objective of this section is to link the index (2.4) with overall performance of bare hulls. The variation of  $Q'$  with respect to  $u$ ,  $v$  and  $r$  depends on hull characteristics. Five hull categories are considered here: tanker, cargo, mariner type, ferryboat and whale ship. The significant parameters defining each hull are listed in table 1.

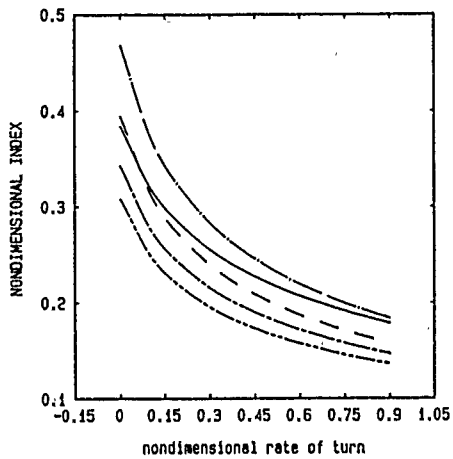
TABLE 2

TANKER	_____
CARGO	_____
MARINER	_____
FERRYBOAT	_____
WHALER	_____

Graphs of  $Q'$  are shown in figures 1-4. The curves in these figures correspond to particular vessels identified in table 2. Figures 1 and 2 display the variation of  $(dv/dr)/L$  with respect to rate of turn for ships operating at drift angle  $\beta = 10$  and  $\beta = 20$ , respectively. In these and subsequent figures the variables are nondimensional with the surge and sway speeds defined by the drift angle ( $u' = \cos(\beta)$ ;  $v' = \sin(\beta)$ ). The values  $\beta = 10$  and  $\beta = 20$  were chosen as representative of ship operations. Inspection of figures 1 and 2 shows that the index decreases with increasing rate of turn for all hull types considered. It is interesting to note that for both drift angles the cargo hull performs like a mariner for small  $r'$  and like a tanker for large  $r'$ .

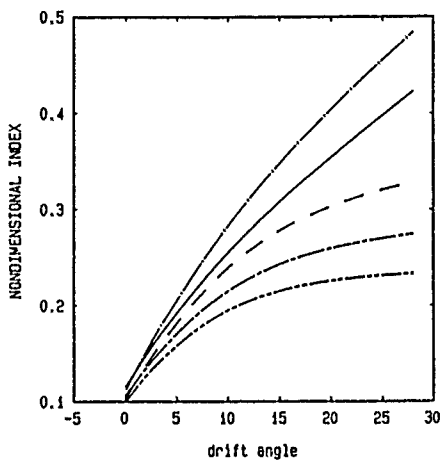
In figures 3 and 4 the index (2.4) is shown as a function of drift angle for fixed rate of turn. The values  $r' = 0.3$ ,  $0.65$  were chosen because the hulls are well differentiated at these points in figures 1 and 2. Inspection of figures 3 and 4 indicates that  $(dv/dr)/L$  increases with increasing drift angle.

FIGURE 1



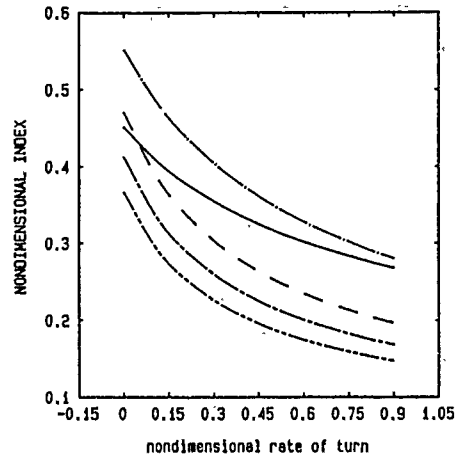
drift angle = 10

FIGURE 3



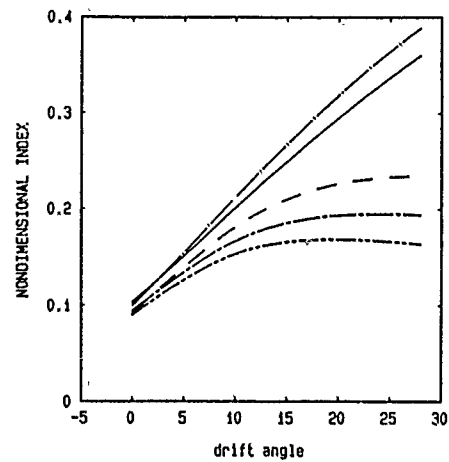
nondimensional rate of turn = 0.3

FIGURE 2



drift angle = 20

FIGURE 4



nondimensional rate of turn = 0.65

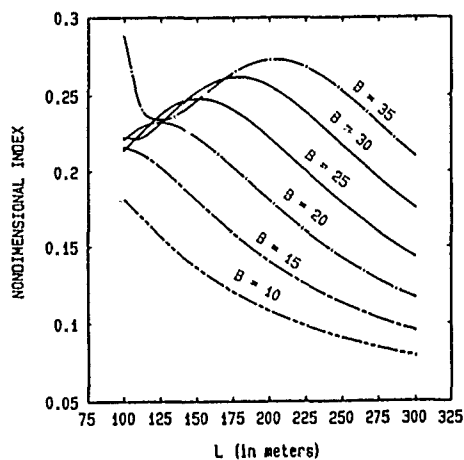
Finally, it is apparent from figures 1-4 that  $Q'$  is larger for tanker and cargo hulls than it is for the other, more maneuverable hulls. The graphical evidence indicates that overall performances improves by reducing the value of  $(dv/dr)/L$ .

## 5. VARIATION OF MANEUVERING QUALITIES WITH RESPECT TO HULL PARAMETERS

In this section  $Q'$  is analyzed with respect to variations in the hull characteristics of the mariner type vessel identified in table 1. Principal hull parameters include length ( $L$ ), beam ( $B$ ), draft ( $T$ ), trim ( $\tau/T$ ) and block coefficient ( $cb$ ), see [5]. The index is studied as a function of these parameters while others, such as aperture of bow and stern, are held fixed. Figures 5-8 display graphs of  $Q'$  for fixed rate of turn and fixed drift angle.

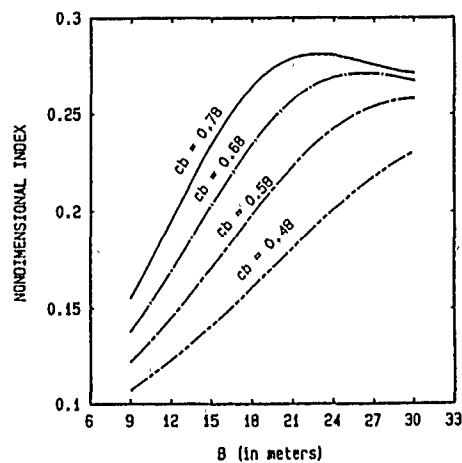
Figure 5 indicates that for typical mariner hulls in the range  $L \approx 160$ ,  $B \approx 20$ , the index decreases as the ratio  $B/L$  decreases. Thus slender mariner hulls tend to preserve their lateral velocity in response to transient variations in turn rate at the drift angle and yaw-rate listed in figure 5. The index is not monotonic for less typical mariner hulls, particularly those that are wide and short.

FIGURE 5



drift angle = 10 nondimensional rate of turn = 0.3

FIGURE 6



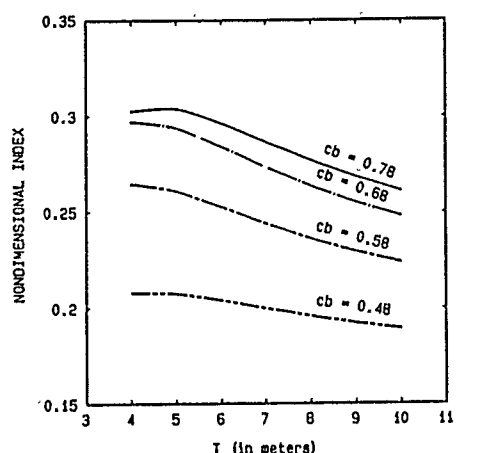
drift angle = 10 nondimensional rate of turn = 0.3

Figure 6 supports the observation that slenderness reduces  $dv/dr$ . It also indicates that  $Q'$  increases with increasing block coefficient. Thus full hulls tend to increase sway in response to transient increases in rate of turn. Figure 7 supports this last observation and also indicates that increasing draft reduces the index. Figure 8 displays the variation of  $dv/dr$  with trim. Hulls that maneuver with their bow deeper in the water than their stern tend to increase sway when yaw-rate is increased, while hulls that



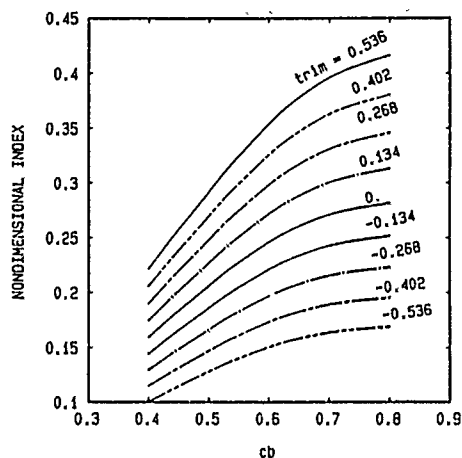
maneuver with their stern deeper in the water than their bow tend to preserve sway.

FIGURE 7



drift angle = 10 nondimensional rate of turn = 0.3

FIGURE 8



drift angle = 10 nondimensional rate of turn = 0.3

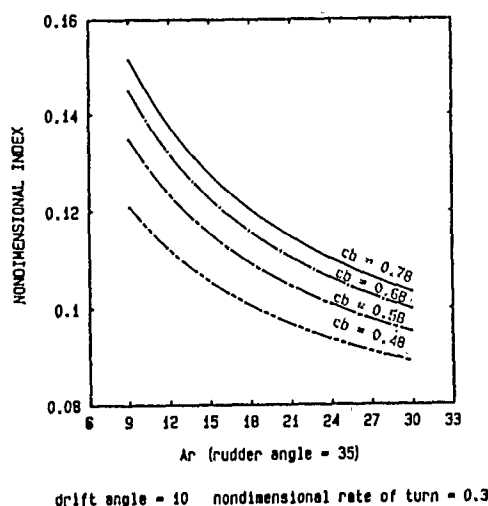
## 6. CONCLUSION

This paper has presented a new index for measuring the maneuvering qualities of ships. The index (2.4) depends on hull characteristics and measures the transient change in sway due to variations in yaw-rate. For a given range of  $u, v$  and  $r$  the index discriminates between ships and ship designs on the basis of whether or not they give rise to a significant change in sway.

The accuracy with which the index can be determined depends on the accuracy of the hydrodynamic coefficients that define (2.3). For a particular hull, small coefficient errors may result in a large index error. For another hull the same coefficient error may have no significant effect on the index. It is therefore important that the hydrodynamic coefficients be determined accurately. In this work theoretical and semiempirical methods have been used to evaluate the  $Q$ , [5]. For the applications presented here, their accuracy has proved satisfactory.

The present discussion has focused on the analysis of bare hulls for preliminary ship design. At an advanced design stage, active controls must be considered. Then the ratio (2.4) involves additional parameters such as rudder number, area and angle. As an illustration, the variation of  $Q'$  with respect to rudder area for a mariner hull with a rectangular rudder is shown in figure 9. The sketch indicates that  $dv/dr$  decreases with increasing rudder area. It also reconfirms the earlier observation that  $Q'$  increases with fullness.

FIGURE 9



Finally, applications of the index include development of maneuvering criteria for ship and port design, restricted waterways management, training and licensing. In ship design the index can be used to develop hulls that change or preserve sway in response to specific variations in  $u$ ,  $v$  and  $r$ . Similarly, prediction of  $dv/dr$  for particular hulls could be useful in the construction of ports. The index can be used to identify those ships permitted to navigate restricted or controlled waterways, and to identify supplementary assistance, such as tugs or experienced pilots, when necessary. The index can also be used to set training and licensing requirements for crews. Officers and pilots could be licensed to operate vessels belonging to specific index categories.

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## NOMENCLATURE

B	: width of hull	$\beta$	: drift angle
cb	: block coefficient	$\tau$	: trim
L	: length between perpendiculars	V	: hull speed
T	: draught of hull (mean)		
$I_{zz}$	: mass moment of inertia		
$J_{zz}$	: added mass moment of inertia		
m	: mass		
$m_x$	: added mass in x-direction		
$m_y$	: added mass in y-direction		
$r$	: rate of turn		
$r'$	: $rL/V$ (nondimensional rate of turn)		
u	: longitudinal component of hull velocity		
$u'$	: $u/V$ (nondimensional)		
v	: lateral component of hull velocity		
$v'$	: $v/V$ (nondimensional)		

## **DEVELOPMENTS IN A DECISION SUPPORT SOFTWARE FOR VESSEL OVERALL CONDITION EVALUATION**

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### **1. SUMMARY**

Recent developments in the expert system VESSELL are presented in this paper. Although the original application of this integrated software was to be used as a decision support tool in ship sales & purchase, the existing structure of interacting Knowledge Bases could be used in a number of other applications :

- For various types of ship surveys
- For evaluation of shipyard quotes for repairs
- For evaluating the condition of machinery systems (such as propulsion system, aux. engines, piping networks), based not only on logged-data and monitoring system output, but also on visual observation and the engineer's past experience with similar equipment.

A ship is modelled as a collection of functional units which can be further subdivided into sub-units, equipment and components down to the level of representation complexity requested by the user during an interactive consultation. This modular structure allows each unit or sub-unit to be considered separately (for example "diesel-generator No2") or several units to be grouped and evaluated together as a larger entity. New items can be added by the user at any level in the internal representation of the ship model, thus offering flexibility and extensibility to the basic software system. Grading attributes for the various items are offered to the user during an interactive session so that the system can obtain adequate information, which can then be used to assist in the condition evaluation of the examined ship units.

The interconnected knowledge bases with information about the functional units and subunits have access to databases for additional information (for example on the cost of repairs of machinery). The report output facility is enhanced by interfacing the expert system VESSELL with commercial editors and spreadsheets.

## 2. INTRODUCTION

The software system described in this paper was originally developed to assist the prospective buyer of a second-hand vessel to evaluate the condition of the vessel and its machinery and, taking into account the buyer's requirements, estimate the necessary cost of repairs. This expert system was meant to be used immediately after a "superficial survey" of a ship and involved an extensive interactive consultation with the engineer who performed the survey.

However the techniques that are used for this evaluation of the overall condition and the output (estimation of condition of specific systems, estimation of cost of repairs) could also be used in other applications.

One potential candidate is an advanced ship's machinery and operations management system. Such systems may include separate modules such as the engine monitoring system (alarms, safety, recording), the diagnosis and trend analysis system, the operation control and various management functions systems (ballast, loading, stress analysis, navigation etc.) . The engine monitoring systems use comparisons between on line data (actual data from sensors) and nominal value data (stored or calculated) and are mainly used as warning systems. Most diagnosis, and trend analysis systems used today in merchant vessels cover only specific sub-areas of diesel engine diagnosis usually presenting a nominal/actual comparison of data, from where trends may be derived. More advanced systems may incorporate a computer model of the monitored system for problem diagnosis and trend analysis. Also a number of "expert systems", have been developed for many parts of the monitoring activities, primarily Knowledge Based systems for machinery fault diagnosis, and also for diagnosis of sensors, as all the data used as input for the systems above are based on online information [1] . One weakness of all these applications is the difficulty of including an overall evaluation of the system, as assessed by a human expert. This cannot be performed on line.

An advanced ship machinery management system could be augmented by a separate parallel "off-line" system that can incorporate past experience as well as include data that are input by an engineer based on his visual or other observations. In this way a complex machinery system (such as the propulsion system, aux. engines) could be evaluated at different levels of detail, but also an overall assessment can be provided. The two systems the "on-line" and the "off-line" can be envisaged to have a symbiotic relation with extensive exchange of information [Fig 1]. By interposing an expert user (engineer), the data input into the off-line system are well qualified and so they could be considered qualitatively more reliable. The user of such a system is directly involved in the data input, thus enhancing data integrity and system robustness.

By using both methods of system condition evaluation (that is from on-line and off-line data) future ship machinery equipment management systems can be greatly improved .

### 3. OBJECTIVES

The decision support expert system described in this paper can assist in the:

- A. Condition evaluation of vessel and machinery systems.
- B. Estimation of necessary costs of repair/conversion.
- C. Evaluation of shipyard quotes for repairs/conversion.
- D. Machinery surveys.
- E. Maintenance scheduling systems

### 4. ARCHITECTURE

For the internal representation within the software system VESSELL a ship is modelled as a collection of functional units, sub-units, systems, equipment/components, down to the level of representation complexity requested by the user during the interactive consultation.

The basic units are the following (Fig 2) :

- 1. General Information (including Certificates/ Classification/ Documents)
- 2. Hull/Deck
- 3. Holds/Tanks
- 4. Propulsion & Aux. Machinery
- 5. Cargo handling gear/Pumps
- 6. Accommodation/Navigation/other equipment.

Each unit is divided into sub-units

eg. 4. Propulsion & Aux. Machinery

- 1. Propulsion System
- 2. Electrical System
- 3. Aux. Systems
- 4. Steering System

A system can be further subdivided into its comprising elements/components

eg. 4.1. Propulsion System

- A. Main Engines
- B. Diesel Generators
- C. Shaft/Bearings/Stern tube/Propeller

Information about each element is stored in one (or more) knowledge bases (K.Bs). Special control K.Bs establish connections and dependencies and also provide special facilities. For example in the case of the diesel generators assessment, an on-top control K.B is invoked that keeps track of the examined diesel generators, sums the separate results and provides an editing facility for the report file.

The communication of information between two related K.Bs is performed via an intermediate file where the results from the consultation of the calling K.B, offered by the user during an interactive session are temporarily stored, before being retrieved by the called K.B.

## 5. REPRESENTATION STRUCTURES / CONTROL MECHANISM

Domain knowledge about each element is represented as a set of facts and rules. Knowledge is also indirectly represented in the question menus. eg. for the assessment of an aux. boiler, the user is asked about the outside inspection he performed to establish the condition of the boiler :

QUESTION: Signs of leaks and/or salt traces were present as...

- wastage around mountings ,
- leaking mudhole door joints ,
- leakage around blow-down cock ,
- other

[Choose one of the above]

The system's control mechanism is basically backward chaining (goal driven reasoning) for the assessment of the various items chosen by the user from the provided menus. Forward chaining rules (data driven reasoning) are used whenever alternative paths must be explored or processes to be executed must be specified (eg. loading of another K.B or providing the user with relevant information saved in a text file).

A more elaborate analysis of the representation and control structures of the system can be found in [2].

## 6. ENVIRONMENT / PHILOSOPHY / INTERFACING

The user is faced with a menu driven environment as he navigates in the tree-structure of units, sub-units, systems, elements, e.g. when at element level in the Main Engines (option A. of Propulsion System) the user is asked :

QUESTION : What do you want to do ?

- assess No1 M/E
- assess No2 M/E
- edit/print the results
- sum the results
- exit to previous menu / propulsion system

For the evaluation of a set of elements of the same type ( eg. No1 M/E, No2 M/E) the corresponding K.B. (eg. Main Engine K.B.) is repeatedly accessed, the results being written to a file for further use, editing, or immediate printing (option "-edit/print the results" above), (Fig. 3).

The distribution of the knowledge to several different K.Bs (domain knowledge about each element usually constitutes one knowledge base), enables useful generalisations to be made in case a quick consultation is required. This is performed without assessing all the elements of a basic unit. Also, by having fewer rules to check in each consultation the system is more efficient. The modular construction of the system, facilitates the evolution of rules during the development and upgrading phases, by making any changes easier to incorporate in the software.

All the results are also saved as ASCII text files and can be called by a Data Base application, that enables the user to customise the format of the output. After possible updating, the information for a certain ship could be saved as a data base file for future use.

The text files containing the results, can also be used as input to commercial spreadsheets in case extensive computations or graphic utilities are needed.

Previous experience and other information related to particular equipment, for example in the form of manhours for repair or specific problems associated with certain types of machinery, can be accessed from data base files or read from ASCII text files. The information for the data base files has been collated using data from shipyards, manufacturers and owners and is parametrised for example by ship size, area for repair, etc. The retrieval of information from the databases is done using an intermediate file, where the results of the query invoked by the system's user are temporarily stored. An in depth analysis of the retrieval procedure can be found in [2].

The present version of the system has been developed on a Prolog based environment and runs on a 386 PC compatible computer. The time needed for a



typical consultation session mainly depends on the level of detail that is needed for the specific assessment and on the number of times data base or other external files are accessed to provide relevant information. While a machinery sub-unit assessment may be completed in a few minutes, the in-depth evaluation of a complete ship would require an interactive session of a few hours.

## 7. ADVANCED FEATURES

a. At various levels of the internal representation of the ship model, new items can be added by the user. That is, the existing control mechanism of the various K.Bs is flexible enough to permit their extensibility. This feature which involves automatic updating of existing question menus and addition of new rules, can also be used during the development or updating phases. For example when at element level in the Diesel Generators (option B. of Propulsion System) the user is asked:

QUESTION : What do you want to do ?

- assess No1 gen.set
- assess No2 gen.set
- assess emergency generator
- assess other gen.set
- edit/print the results
- sum the results
- exit to previous menu / propulsion system

By choosing the fourth option "-assess other gen.set" the user can update the menu above to include an extra gen.set (No3 gen.set).

QUESTION : What do you want to do ?

- assess No1 gen.set
- assess No2 gen.set
- assess No3 gen.set
- assess emergency generator
- assess other gen.set

.....  
By choosing the option "- assess No3 gen.set" the user can immediately proceed to the evaluation of No3 gen.set in the same way as in the case of No1 and No2 gen.sets. New rules have been automatically added to the system in order to accommodate the new item's information in the grading system and the printed report. The changes in the K.B are saved on request.

b. For the condition assessment of complicated machinery such as the main engine or the diesel generators a 3-level weighting factor system is used [Fig. 4]. This can be more easily understood through an example.

In the case of the main engine assessment the user can input information about:

- operational characteristics ,
- engine measurements
- spares availability
- consumptions
- other

[Multiple choice]

The "measurements" have different weighting factors from the "consumptions" or the "spares" (1st level).

In the case the user wants to input information about the "measurements" he can choose from a menu of the form :

- cranksaft
- bearings
- liners
- other

Each of the items in the above menu has also different weight with respect to the others (2nd level). This "knowledge" is embedded into the system. The information the user gives, is related to the condition of specific items in the second level menu, is qualitative e.g. excellent, good, requiring renewal and is provided from menus of the form:

QUESTION: How would you describe the oil pressure?

- high
- within acceptable limits
- low
- other

[Choose one of the above]

Each option in the above menu has a different weighting factor (3rd level). If the user offers specific information (eg. a "low" value) in this 3rd level of detail, this may trigger different sets of weighting factors for the two upper levels. In the case above, if the user offered the information that the cranksaft required renewal this would trigger different values than the default ones, for the weighting factors of the "measurements" and the "cranksaft" in relation to the other elements of the 1st and

2nd level menus. Since this problem affects very seriously the main engine assessment, there are specific rules included in the software that are triggered when such information is received.

If required, the embedded knowledge can be concealed from the end user, eg. if it reflects the policy of the company or the technical director, and it is not to be made public.

Work is currently in progress in the area of updating automatically this embedded knowledge about the weighting factors through an interactive consultation with a "qualified" person. In the case of a "new" item, it is not at the moment possible to establish during a consultation the interconnections with existing items, so that the interrelations of the weighting factors can be automatically generated. The facility of automatic updating the K.B, will normally be unavailable to an end user who has no knowledge of the underlying weighting philosophy.

It must be noted that the appropriate values of the weighting factors can only be defined after extensive experimentation to obtain acceptable results.

During a specific consultation, the user can either accept the grade provided by the system which is based on the input information, or he can modify it so that a corrected value is used for the overall unit assessment.

## 8. CONCLUSIONS

In this paper the recent developments of the software system VESSELL have been discussed. This system, in addition of being a decision support tool for evaluating the condition of a ship and its machinery, could also be used in parallel with monitoring and trend analysis systems, as a part of an advanced ship's machinery and operations management system.

In the case of interaction with a monitoring system, the operator, in case of a fault, can also have access to information about the condition of specific machinery, in the form of results from past interactive consultations using VESSELL. In this way, the sources of information on which a decision will be based, are extended.

In the case of an interaction with a trend analysis system, the results of previous consultations can be provided, in addition with other useful information eg. spares availability and cost of repairs, so that maintenance scheduling and operations may be optimised.

In the present phase of development, most of the interconnected K.Bs have been completed. Self contained parts of the software which can evaluate separate units and sub-units in a high degree of detail can run independently. The overall package can also run for a superficial survey of a complete ship.

## GLOSSARY

### Backward chaining (or goal directed control strategy)

In goal directed reasoning a system starts with a statement of the goal to achieve and works "backwards" through inference rules, ie from right to left, to find the data that establish that goal [3].

### Data-driven reasoning

Data driven means "inferred from the input data" [4]

### Forward chaining (or data directed inference)

The data that are known, drive the inferences in rules from left to right, with rules chaining together to deduce a conclusion [3].

### Data base file

File containing the data and the database structure.

## ACKNOWLEDGEMENT

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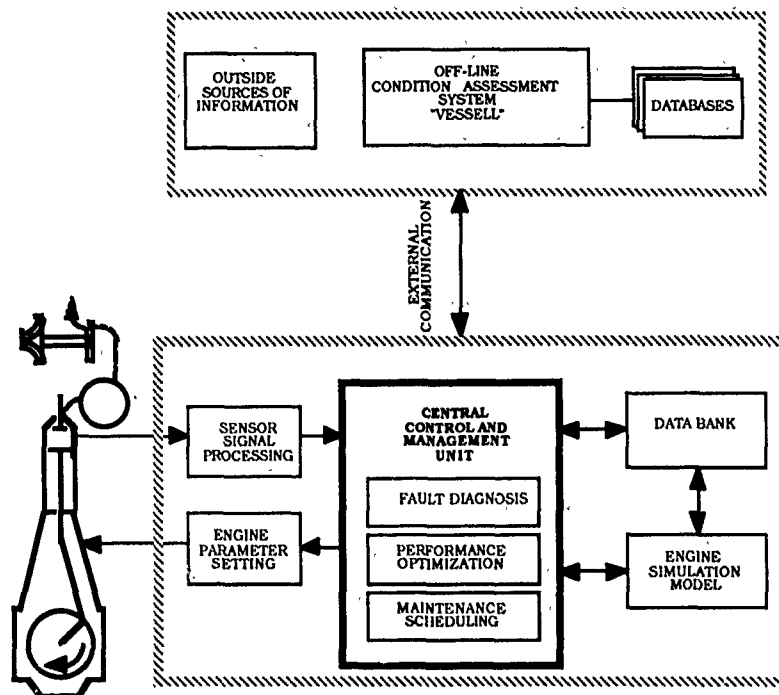


Fig. 1 Advanced ship machinery management system.

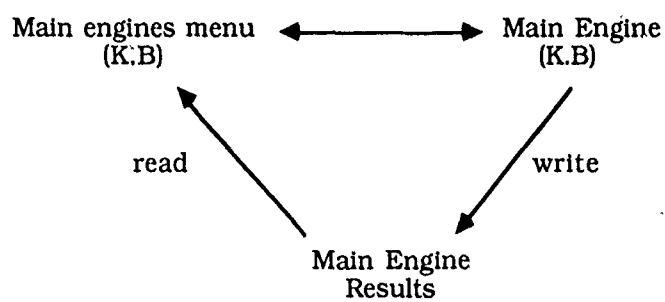


Fig. 3 Program structure for main engines assessment.

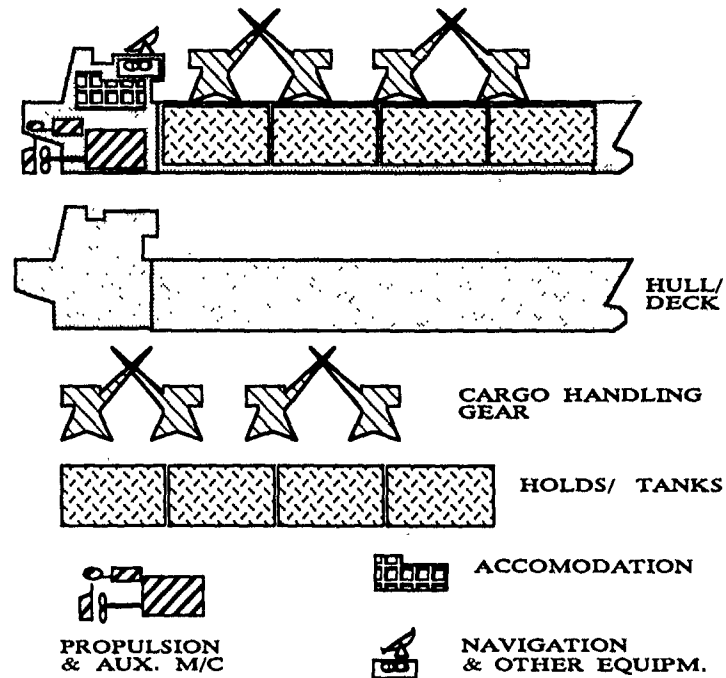


Fig. 2 Basic units in model of typical ship.

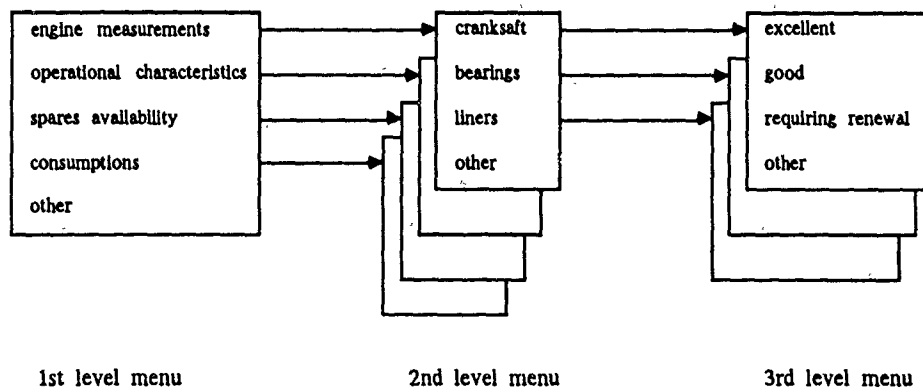


Fig. 4 The 3-level menus used in the weighting factors system.

**DAMOCLES:  
AN EXPERT SYSTEM FOR DAMAGE CONTROL MANAGEMENT  
ABOARD STANDARD FRIGATES**

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**1. ABSTRACT**

Under commission of the Royal Netherlands Navy TNO Physics and Electronics Laboratory is developing Damocles, a Damage Monitoring and Control Expert System. Damocles is an artificial intelligent decision support system to be used by the damage control organisation aboard Standard frigates, in particular the damage control (DC) officer. It offers the DC-officer an integrated collection of tools directed at fire-fighting, damage control and maintenance of ship stability. The aim of developing and introducing Damocles is to improve and quicken the decisions concerning (re-)configuration of technical systems in the case of a calamity.

**2. INTRODUCTION**

TNO Physics and Electronics Laboratory, in collaboration with the NBCD School of the Royal Netherlands Navy, is developing Damocles, a Damage Monitoring and Control Expert System. The main purpose of the Damocles project is the development of an expert system which supports the damage control (DC) officer aboard Standard frigates in maintaining the operational availability of the vessel by safeguarding it and its crew from the effects of weapons, collisions, extreme weather conditions and other calamities. Basically DC-management includes the classical command and control cycle: status maintenance, situation assessment, planning, tasking and evaluation. An important way of making the total DC-organisation more effective is to improve the quality of the decision making process by providing automated decision aids to the DC-officer in addition to the information processing and presentation facilities already available [1]. This applies especially to damage assessment and planning.

The DC-officer on board navy ships is part of the organisation of nuclear, biological and chemical protection and damage control (NBCD). When a calamity has occurred it is very difficult to collect all relevant information concerning the calamity, to structure and interpret the acquired information in order to find a solution for the problem and to ascertain what influence the calamity has on the operational availability of the vessel.

The experience of the DC-officer is very important in the management of DC-situations. The DC-officer must not only consider actions that provide short-term solutions for problems, but also assess the long-term consequences. Due to the nature of DC-situations NBCD-management has to make decisions in

a short time frame and under stressful conditions. These decisions are very often based on incomplete information of a complex technical system (S-frigate). When a wrong decision is being made, the consequences can lead to more serious damage as was initially the case. A decision support system can play a crucial role in this kind of situations. The functioning of such a system is dependent on the availability of (technical) knowledge about the structure of the ship and its subsystems, knowledge about the state the ship is in, knowledge about procedures which have to be followed (laid down in documents) and the experience of DC-officers.

More and more conventional systems contain intelligent modules, without the assurance that these modules satisfy the same rigorous quality measures as the conventional ones do. In comparison with conventional software systems the quality of expert systems is viewed as not being very satisfactory. Some of the more problematical aspects are knowledge acquisition, testing, evaluation and the maintenance of the knowledgebase. As yet there is not much unanimity with regard to the ways in which these problems have to be tackled. This is an objectionable state of affairs, especially when you are dealing with critical applications, e.g. process control systems in industry or nuclear power plants.

The same argument is also valid for military Command, Control, Communications and Intelligence (C<sup>3</sup>I) systems [2]. A characteristic of these systems is that they consist of large databases with which the deployment of men and material is coordinated. Starting point of this discussion is the thesis that a knowledgebase can be viewed as a collection of facts which can be manipulated with intelligent rules. These rules are also stored as objects in the knowledgebase [3]. An additional convenience of integrating an inference engine with such a database system is that facilities as integrity, concurrency, security, recovery and distribution can now be used inside what we call a knowledgebase system, or expert system [4]. The main theme of this paper is that the integration of database theory and artificial intelligence signifies a step in the direction of a better quality control of expert systems.

In this paper four topics will be discussed. After the introduction we give an overview of damage control management, followed by a description of the Damocles system architecture, conceptual modelling of the knowledge domain and the integration of artificial intelligence and database technologies.

### 3. DAMAGE CONTROL MANAGEMENT

#### 3.1 Problems encountered in damage control management

In case a calamity has occurred, the DC-officer has to collect and combine data from different sources (sensors, communication systems, orderlies etc.) in order to assess the situation. On the basis of this, the DC-officer plans actions and looks after the careful execution of these actions. There are a number of problems interfering with the decision process: complexity of the vessel, uncertain and incomplete information, time pressure and catastrophic effects of wrong decisions. The DC-officer can only carry out his duty when he has a lot of experience with the vessel and the procedures which have to be executed.

The DC-officer takes charge of combating a calamity from within the ship control centre (SCC), which can be compared with an operator room in a power plant. After a missile hit various ship systems could have sustained damage. At this moment the DC-officer has to take a number of decisions, e.g. concerning the high pressure sea-water system (HPSW, or firemain). How should this system consisting of pipes be (re)configured in order to simultaneously support one or more fire and repair parties (FRP), isolate leakages, keep critical systems (sprinkler, cooling) under pressure and remove inflowing water with bilge-pumps? A more general question could be: What are the relative priorities between attacking a fire, drain off water from compartments or even flooding them (to preserve ship stability)? Each of these problems



can be solved easily when they occur in isolation. When a DC-officer is confronted with several of these problems at the same time, he has to weigh one counter-action against another [1].

While executing his task a DC-officer encounters the following problems: complexity of technical systems, incomplete information, stress and lack of experience.

a. Complexity of technical systems. Despite extensive documentation, the systems on board an S-frigate are not easily seen through.

b. Incomplete information. The communication on board a ship often takes place under difficult circumstances (noise, smoke, water, confusion) and is therefore not optimal (correct information can get lost, incorrect or redundant information can be created).

c. Stress. The time pressure is high, because a DC-officer has to take a number of decisions (possibly with great consequences) in very little time.

d. Lack of experience. In order to correctly fulfil his duties a DC-officer must not only have at his disposal an extensive knowledge of the ship and procedures, but also knowledge based on experience.

In brief, it requires a certain amount of experience to make correct decisions in a short time frame, based on incomplete information.

### 3.2 Damage control tasks

The following DC-management tasks can be identified: detection, data fusion, damage assessment, planning and plan monitoring.

a. Detection. Detection of significant events occurring within the ship or one of its subsystems. Detection can be done by automatic means (sensors) or by human observers. Events of interest are the presence of water, smoke (digital signals) or the value of a temperature, flow, pressure (analogue signals). It is important that these events are notified to the DC-officer.

b. Data Fusion. Usually an event is detected by more than one sensor. Also detections at different points in time may refer to the same event or a set of causally related events. Different sensors provide a different view of the event, with different levels of detail and accuracy. It is essential to fuse all this information into one "objective" picture of the situation: the actual system status.

c. Damage assessment. After having established the ship's status, it is very important to realistically assess the damage of the ship, i.e. evaluate the short term as well as longer term consequences for the ship and mission. Various hypotheses have to be formulated and evaluated and the most likely events have to be predicted.

d. Planning. After having assessed the damage and its probable consequences, actions have to be planned to combat the incident. These actions depend on overall directives from the ship's commander, the desired and actual situation. Actions may range from the closing of a valve to the tasking of a fire and repair party (FRP) to undertake some specific activity. Often alternative courses of action have to be formulated and a decision made in a short time frame. This task also includes the allocation of resources to the various actions.

e. Plan monitoring. The evolving situation has to be monitored continuously, to verify that the conditions for the plan still hold and that progress is being made. If not, other actions might be more appropriate. During the execution of combat actions, priorities may change. Input to this task are all the incoming signals and reports. Thus this task is closely related to the data fusion task. To be more precise, the tasks described form a cyclic process.

#### 4. ARCHITECTURE OF DAMOCLES

##### 4.1 Overview

The Damocles project started with a detailed task analysis of the DC-officer in which the following main task areas were identified: stability monitoring and the prevention and repression of fire and damage. The Damocles system assists the DC-officer in these tasks, most notably the evaluation of the situation (system monitoring and diagnosis), determination of the measures to be taken (planning) and monitoring of the execution (plan-monitoring).

With regard to Damocles two kinds of requirements can be distinguished: functional and operational. Functional demands lay down the functionality of the system, operational demands specify aspects which are of importance when the system is in operational use. The following functional requirements did receive much attention:

- To support fire-fighting, damage control and the maintenance of ship stability,
- To simulate technical systems aboard an S-frigate and
- To query an intelligent database.

The architecture of Damocles is set up along the lines of the so called second generation expert systems. These systems can not only suggest solutions on the basis of heuristics, but can also reason with more fundamental knowledge. Therefore Damocles has at its disposal: knowledge about the structure of the vessel and its subsystems, knowledge about the actual state of the vessel, knowledge about the desired state of the vessel, knowledge about the working of subsystems, knowledge about procedures to be followed and knowledge based on experience of DC-officers. The first three types of knowledge could be called declarative, the last three procedural.

Damocles can be divided into two layers. An under-layer consisting of modules that represent specific subsystems and an integrating upper-layer of modules that support the DC-officer in his duty (and uses the modules in the under-layer). The upper-layer contains the following modules:

- Fire-fighting,
- Damage control and
- Maintenance of ship stability.

The subsystem dependent under-layer contains the following modules:

- Ship,
- Sea-water systems:
  - Firemain,
  - Foam systems,
  - Sprinkler systems,
  - Dewatering systems,
  - Trim systems,
  - NBC prewet system,
  - Cooling systems,
  - Sanitary systems,

- Halon systems,
- Ventilation system,
- High pressure air system and
- Fuel load and transport system.

The interface between Damocles and the DC-officer has been given much attention. The DC-officer can make use of a number of technical systems. At present a prototype of Damocles is running on a Sun-workstation equipped with a colour graphic display in order to present images of underlying technical ship systems (e.g. ventilation and HPSW). These images consist of 2-dimensional representations of pipe networks containing all relevant information required for monitoring and control of these systems. In addition to this, a 3-dimensional image of the ship with overlays of technical systems is used to convey spatial information. On-line manipulations can be made to simulate the consequences of decisions. Usually these decisions are made by inspecting complex lay-out schemas and diagrams which show where pipes are running and how they are connected, etc. Damocles offers the opportunity to simulate the earlier mentioned technical systems and it gives concrete solutions for certain problems. This is realized by reasoning on the basis of structural and functional information about the system components.

#### 4.2 Damocles system tasks

The following functions can be identified for the decision support system (comparable with the DC-management tasks): monitoring state of ship, diagnosis, prediction of consequences of problems or causes, planning of actions, execution and monitoring of chosen plan, prediction of consequences of possible orders. In the following paragraphs these tasks are described in more detail.

a. Monitoring state of ship. This task should observe state variables and compare them with their norms. The collection of norms forms the goal state of the ship. The diagnosis task is activated if there are discrepancies between variables and their norms. There is a discrepancy if the norm for the state of a valve is open and the real state of that valve is closed.

b. Diagnosis. This task tries to find a cause for the discrepancy. If there is no pressure in one pipe, the cause can be a malfunction of a pump or a leakage in a pipe.

c. Prediction of consequences of problems. The impact of problems on the state of the ship has to be predicted to give those problems relative priorities. Fire in an ammunition store receives a higher priority than a loss of water pressure in a lavatory.

d. Planning of actions. To solve a problem or minimise the impact of it, actions have to be executed. Thus one has to synthesize a plan, a collection of successive actions. This is a kind of state-space search, in which the goal state is described by a collection of norms. The plan has to be optimised, the effort to achieve it has to be minimised.

e. Execution and monitoring of chosen plan. If there is a plan the actions have to be executed in the right order. This task monitors this process, e.g. a pump cannot be switched on before it is initiated.

f. Prediction of consequences of possible orders. If one changes a norm, one introduces discrepancies, new problems, new consequences and new actions to be executed. So, before changing a norm the consequences have to be predicted and a confirmation of the user is required. This is to prevent the user giving orders to the system with unforeseen consequences.

Artificial intelligence provides the tools and techniques to use effectively the knowledge about the vessel and to accept, combine and fuse the data from sensors and reports [5].

## 5. CONCEPTUAL MODELLING

Expert systems are often developed with rather exotic methods and implemented in an AI-shell. This causes a number of problems; how can the expert system be embedded in other software, what communication links are possible and where do we get system developers who are acquainted with the used methodology? It is our conviction that these problems can be alleviated by using the relational model. E.g. coupling an expert system with an existing C3I-system or RDBMS should be easy. Already during the specification of the knowledge, conventional system analysis and design methods can be used. The system can also be implemented with tools of established reputation. A big advantage of the relational model is the fact that very complex models and manipulations of data (and rule) sets can be defined with a limited number of concepts and operators.

Damocles contains models of several technical ship systems. These models can be used in different ways:

- To simulate the system or train students: What would happen if?
- To search for faults in the system (diagnosis) by comparing the functionality of the model with the reality
- To make statements about partially observable systems; The status of the system is represented in the model. The observed status can be compared with the model status. If there are discrepancies the model status needs to be adjusted. By using a model one can make decisions about a technical system, even when the information on hand is incomplete.

The conceptual model has to be a complete and consistent representation of a knowledge domain in which a distinction is made between a knowledge scheme (definitions of all used facts and relations) and the actual knowledgebase. This distinction can also be seen as a separation of types and instances. Consistency and completeness can be maintained by means of constraints on the actual knowledgebase. A conceptual model has to be constructed with a development method that lays down explicitly the definition of facts and their interrelations. In an AI-methodology like KADS (Knowledge Acquisition and Structuring) four levels of knowledge are being distinguished [6]: domain, inference, task and strategic levels. NIAM, Nijssens Information Analysis Methodology, and ExtendedNIAM, can be used to structure these four levels of knowledge [7,8,9]. On the domain level the basic elements and their interrelations are specified. The inference level contains the inferences which can be initiated based on the domain level. The third level of knowledge is the task level, which specifies process structures and tasks. This level is specified with the use of KADS. The resulting conceptual model is laid down in a relational data structure. The fourth knowledge level is not used in the Damocles system. By using (E)NIAM the quality of extensive data- and knowledgebase specifications is guaranteed.

## 6. INTEGRATING ARTIFICIAL INTELLIGENCE AND DATABASE TECHNOLOGIES

### 6.1 From database to knowledgebase

Relational database management systems (RDBMS) are primarily being used for administrative applications. Concepts like data independence, data integrity, controlled redundancy, security and privacy are also very important when you are dealing with knowledgebase management systems (KBMS). Other reasons to adhere to the relational model are its conceptual simplicity and the fact that system developers are familiar with it. Most software producers are more experienced in using Oracle and Ingres rather than Lisp, Prolog or AI-development tools like KEE, ART or Knowledge Craft. Moreover it is not easy to become acquainted with such advanced tools. By using an RDBMS update anomalies and

redundant storage can be prevented. It also offers a flexible growth path when operational concepts are changed or data structures are modified.

When a knowledgebase is viewed as a special kind of database, various facilities of DBMSs could be used in KBMSs. Examples are recovery (to restore a knowledgebase after a calamity, fault or power failure), concurrency (simultaneous utilization of a knowledgebase by different users), distribution (physically distribute a knowledgebase over different locations), security (protect a knowledgebase against unauthorized usage) and integrity (guard against inconsistencies of the knowledgebase) [4]. Especially this last point enables a direct relation with analysis and design methods of databases. Consequently, there is a need to build a conceptual model of a knowledge domain. A conceptual model can be placed between the internal model of a knowledgebase (the way in which the relations are physically represented) and the external model (the way the user sees the system).

An obvious choice for the representation of a conceptual model of reality, represented with NIAM, is a relational database. This implies that the domain and inference level can be implemented in a relational database. The procedural level has to be represented preferably in a relational programming language: Prolog is a logical choice. Most RDBMSs can be approached by means of the standard interface and query language SQL (Structured Query Language). This leads to hardware and operating system independent storage systems. Different kinds of software can be integrated when the interfaces between them are implemented with SQL.

One of the programming languages used in artificial intelligence research is Prolog (Programming in Logic). This language bears much resemblance with relational systems and can therefore be used to implement a model which consists of relations. Prolog can be viewed as a relational query language, because it is based on relations and contains relational operators. It differs from an RDBMS with respect to the manner in which data is being stored: Prolog rules and facts are placed in internal computer memory and not in files. Prolog is not only a query language, but also an implementation language that can be used to develop software systems. Prolog has considerably more potential than SQL (the use of recursion) and other programming languages (meta-programming facilities). There are also parallel versions of the Prolog language. Deductive database systems, also called expert database systems or knowledgebase management systems, combine the features of RDBMSs and logic programming languages.

## 6.2 Architectures for knowledgebase management systems

Several proposals have been made with respect to the architecture of knowledgebase management systems (KBMS). Often a distinction is made between loosely-coupled and tightly-coupled KBMSs [3].

A loosely-coupled KBMS is an external database management system (DBMS) that is interfaced with a logic programming language: e.g. the Oracle DBMS coupled with the logic language Prolog. Prolog-rules in this configuration can activate queries on the database.

The possibilities of a combination of a relational database and Prolog surpasses those of conventional AI engineering environments. TNO Physics and Electronics Laboratory uses an integrated development environment consisting of Oracle, Quintus Prolog and ProWindows (a Prolog based tool for making graphical interfaces) to realize the Damocles project. The following extras can be envisaged:

- Check on the consistency of knowledge,
- Secure the knowledge against unauthorized usage,
- Distributed storage of knowledge,
- Multitasking and distributed processing,

- Recovery facilities and
- Availability of many development tools.

In a tightly-coupled KBMS there is no distinction between a database system and a logic language, i.e. the strict distinction between database operations and the inference mechanism is abandoned. This can be realized in two ways: Firstly a logic language can be extended with database facilities like integrity, concurrency, security, recovery and distribution. Secondly a DBMS can be extended with deductive (Prolog-like) facilities. An interesting example of this architecture is Postgres, a further development of the DBMS Ingres (Post Ingres) [10,11].

Postgres is a tightly-coupled KBMS developed at the University of Southern California, Berkeley. The main aims of the project are to uphold the relational model and to provide facilities for "active" databases and inference, including forward and backward reasoning. In many applications it is very convenient to use triggers and alerters. Triggers are small pieces Structured Query Language (SQL) program which can be activated when changes are being made in the database (e.g. insert, delete or update). Alerters are comparable with triggers, but are activated by time or date.

The most revolutionary aspect of Postgres is the use of rules and procedures as if they were plain data items. Nijssen views an expert system as a system that contains human expertise and consists of a collection of related facts [7]. These facts can be inserted by a user, or can be derived by the system itself on the basis of other facts and inference rules. Rules in Postgres can perform forward and backward chaining. This can be achieved by "early" and "late" evaluation. In the case of early evaluation a change in a data item that is contained in a rule will directly lead to activation of this rule. In the case of late evaluation the change only becomes obvious when a user queries that particular data item.

When inference rules are used in a KBMS, it is possible to perform a run-time "computation" of a relation. In other words the system has at its disposal an intension of the application (definition of tables, mutual dependencies and inference rules) and when necessary computes the extension (the actual facts in tables). When simulations are being executed (planning task) it is also possible to store different system states in separate databases.

## 7. CONCLUSIONS

A relational database enhanced with Prolog offers good opportunities for the transparent development of extensive and highly qualitative expert systems. The usefulness of artificial intelligence and expert systems in DC-management is demonstrated by the development process of the Damocles system.

Damocles offers the following advantages:

- Quicker and better decisions in the case of a calamity
- Easy to extend with other types of technical system (e.g. electrical system or weapons system)
- Modular structure eases the incorporation of other types of vessel (e.g. Multi-purpose frigate, Guided missile frigate, container ships) or even another type application (e.g. power plants, management of communication networks)
- Optimal portability to other types of hardware as a result of the chosen software tools (Oracle, Prolog)
- Not only intended to be used aboard navy frigates, but also in training surroundings at the NBCD-School
- Not susceptible to (battle)stress.

For the sake of completeness a few words have to be said about the limitations of Damocles. The operational requirements were not important during development of the prototype system. That is why the system is not mil-spec or real-time. At the moment there is also no direct coupling with the various sensor systems aboard the S-frigate. However, these and other aspects of developing an operational system to be installed on every S-frigate are of later consideration. The first step in this direction will be the incorporation of Damocles in a simulator of the S-frigates SCC, which is placed in the NBCD-School in Den Helder, The Netherlands. After an extensive evaluation and test of the system (beginning in October 1990) a decision has to be made whether Damocles will "go to sea".

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# **AUTOMATIC NAVIGATOR-INCLUDED SIMULATION FOR NARROW AND CONGESTED WATERWAYS**

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## **1. ABSTRACT**

A method of fast-time simulation including a navigator's model is proposed. This method is an application of Ship Auto-navigation Fuzzy Expert System (SAFES) and in this paper some considerations and modifications necessary for applying it to harbour and waterway designs are described. An example actually used for a certain bypass design of a particular congested waterway is shown and it is verified the system is useful for these applications.

## **2. INTRODUCTION**

When a new harbour or a waterway is designed, it is, of course, necessary to take care of the natural configuration and environmental conditions as well as the particulars of the considering ships. In straight waterways or waterways with low traffic density, however, some simple formulae constructed mainly by principal dimensions are usually used to determine the waterway width[1]. In bent waterways or waterways with frequent traffic, we should further take care of more detailed manoeuvring performances of the considering ship, human behaviours, and even motions and behaviours of other traffic vessels.

For this purpose, safety assessment using a ship handling simulator plays an important role. The problem in this case lies rather on the psychological effects concerning to the visual display etc. and the experiment costs. Furthermore, the traffic effect is usually difficult to implement, although the author and others have proposed a methodology realizing intelligent movements of target ships in a ship handling simulator[2].

Thus, the demand is growing for fast-time simulation with more realistic navigator's model to assess safety navigation of new harbours and waterways, or to select suitable scenarios for real-time simulator experiments. In the fast-time simulation technique, the mathematical model of the ship dynamics in various environmental conditions should be of course carefully investigated, but the modelling of a navigator is another important factor



especially for narrow and congested waterways. On the other hand, automation in ship navigation is coming to new age of "intelligent ships". Here, the key point of intelligent ships is again how to represent and integrate navigator's knowledge and experiences.

The author has already proposed a basic model of navigators necessary for from usual navigation to collision avoidance[3] and an expert system approach to collision avoidance in multi-ship encounters has been also proposed by Koyama *et al.*[4]. In the system called SAFES(Ship Auto-navigation Fuzzy Expert System)[5], both are combined and revised more suitable for applications to narrow and congested waterways. There are already two actual applications using SAFES. One is realistic simulation of marine traffic flow in the one of the most congested waterways in Japan, where over 600 vessels in a day are passing and crossing in a #-shape waterway. The other is done to design a bypass waterway, even which is very narrow and bent, and has strong current. In the paper, the micro simulation technique including navigator's skill is to be described with full reference to the latter application.

### 3. SHIP AUTO-NAVIGATION FUZZY EXPERT SYSSTEM (SAFES)

The system itself[5] is an expert system written in OPS83. In the system, the basic subsystem is the modelling of behaviours of a navigator and a helmsman including collision avoidance with one target ship[3]. Though the subsystem was converted to C from FORTRAN77 and if-then type rules especially for collision avoidance were extracted to implement into an expert system, there are only a few modifications from the original version of a navigator's model[3]. In this section, the system will be described briefly with explanation of revised or modified points.

#### 3.1 Modelling of a navigator

The following items are all modelled using fuzzy theory.

- **Fear of collision** is reasoned from TCPA (Time to the Closest Point of Approach) and DCPA (Distance of the Closest Point of Approach) as same as the original version[3], but the maximum values of the membership functions are modified so as not to *feel* the fear of collisions in normal sailing condition within the given waterway.
- **Path keeping.** The course changing point is assumed as a buoy and the nearness to the buoy is reasoned just as the analogy to the fear of collision. The maximum values of the membership functions are also modified to match the waterway width and curvature. According to the nearness to the course changing point the course command is reasoned from the course to the course changing point and the course to the next course changing point. This controller is especially useful for narrow and bent waterway navigation, because we need only input some points on course changing points, but not the points of starting the course changing. The controller automatically order the necessary rudder commands at proper timing, even if the ship is sailing off the designed path. Figure 1 shows an example of input points for path keeping.

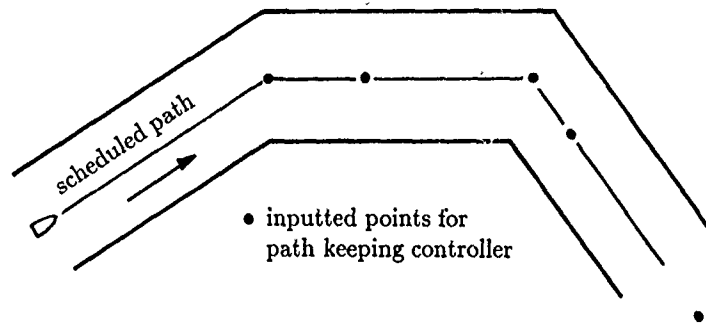


Figure 1. Example inputs for path keeping controller.

- **Course keeping/changing.** From the inputs of heading error and rate of turn, the output of rudder angle is reasoned. This fuzzy controller — called *fuzzy autopilot* — is superior in smooth change of its control gain from course keeping to course changing.
- **Waterway boundary detection** is a new feature provided for narrow and bent waterways. As shown in Figure 2, false-ship concept is introduced to detect the boundary. In Figure 2 (a) false-ships are placed on the crossing point of the nearer boundary with heading course and on the boundary aside of the own ship respectively. In the case as shown in Figure 2 (b), only the side false-ship is placed. After placing false-ship(s), we no longer take care of the boundary itself, and false-ship(s) are regarded as usual ships except the following limitations.
  - The false-ships are created, when there are crossing points between the *true* ship and the boundary.
  - Otherwise, the false-ships are removed from the working memory.
  - The false-ships move only along the boundary according to the movement of the accompanying *true* ship.
  - The false-ships themselves take no action for collision avoidance with the accompanying ship, nor other ships including other false-ships.

The false-ships themselves have no *fuzzy* effect, but the fear of collision to the boundary is again reasoned *fuzzy* using the false-ships.

Calculation of crossing points including parallel condition between a given point (the *true* ship) and a polygon (the waterway boundary) is unexpectedly troublesome. A set of subroutines to handle picture interference as shown in Table 1[6] is useful for this purpose, because it can even check if any part of the ship outline touches the boundary or if the ship is inside the waterway.

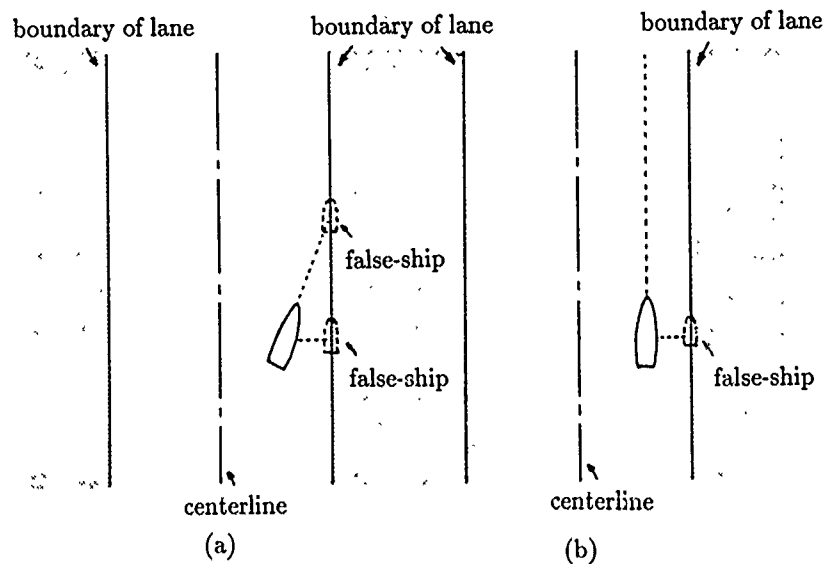


Figure 2. False-ship concept to detect waterway boundary.

Table 1. List of functions for picture interference perception[6].

Name	Function
line-length	to calculate length between two points
line-crossing-point	to calculate a crossing point of two lines
line-crossing-angle	to calculate angle between two vectors
check-point-on-line	to check whether a point is on a line segment or not
check-line-parallel	to check whether two lines are parallel or not
check-line-cross	to check whether two line segments are crossing or not
check-line-touch	to check whether two line segments are touching or not
check-point-on-polygon	to check whether a point is on an edge of a polygon or not
check-point-include	to check whether a point is included in a polygon or not
check-polygon-cross	to check whether two polygons are crossing or not
check-polygon-touch	to check whether two polygons are touching or not
check-polygon-include	to check whether a polygon is included in the other or not
check-interfere	to calculate <i>spatial distance</i> between two polygons

### **3.2 Expert system approach**

Even if elemental models of a navigator are obtained for various navigational situations, it is not convenient to describe all possible combinations of situations using conventional programming language. Expert system is suitable for these applications and OPS83 is one of the tools to describe an expert system.

**a. Working memory configuration.** In OPS83, the working memory configuration or definition of *elements* is important. In the system SAFES, the following elements are defined.

- **ship** element expressing each ship with information of
  - physical features
  - state of navigation
  - state of motion
  - state of avoiding action plan.
- **target** element being created if any two ships *feel* the fear of collision and being removed if the fear disappears. It contains information about
  - own ship's number and other necessary states
  - target ship's number and other necessary states
  - fear of collision.
- **if-target** element being used for determining the timing of returning to the original path during avoiding. It contains
  - own ship's number
  - target ship's number
  - fear of collision, if the own ship now changes the course directing to the original path.
- **obstacle** element indicating the boundary of a waterway
- **start** and **goal** elements being used for the process control

**b. Knowledge base.** Knowledge base is a collection of rules which contains

- rules for process control
- rules for simulation control including graphic display
- rules extracted from regulations such as International Regulation for Preventing Collision at Sea

- rules extracted from a navigator's model
- other implicit rules such as
  - "Do not overtake a ship which is overtaking, but reduce speed".
  - ...

**c. Graphic display.** Graphic display is a good interface showing the system status and the results. In the system **SAFES**, graphic windows are divided as follows:

- **absolute plot window** which shows the bird's eye view with the traced positions of each ship
- **relative plot window** which shows the traced radar's view of a particular ship specified by an operator
- **perspective view window** which shows the perspective view from the bridge of the specified ship
- **console window** which shows various information such as the present rudder angle of the specified ship or the fear of collision between a certain ship etc.

The graphic displays are created by setting *cameras* suitable for each window and the graphic data itself is unique in the system. Recent graphic workstation (GWS) has such capability with standard graphic subroutines. An example of multi-ship encounter is shown in Figure 3, where absolute plot and four relative plots windows are used.

#### 4. APPLICATIONS OF SAFES

As **SAFES** itself is a navigator's model in multiple ship environment and contains simulation capability, it can be applicable to various problems such as

- fast-time simulation to
  - design or assess narrow and bent waterway navigation
  - provide scenarios for ship handling simulator experiments
- generation of realistic traffic environment to
  - evaluate of an automatic navigation system or a vessel traffic system
  - provide visual and radar background of a ship handling simulator[2]
  - evaluate or predict traffic environment itself for waterway design[7].

In this section, two of them carried out for actual projects will be introduced to show the effectiveness of **SAFES** and the future problems to be revised.

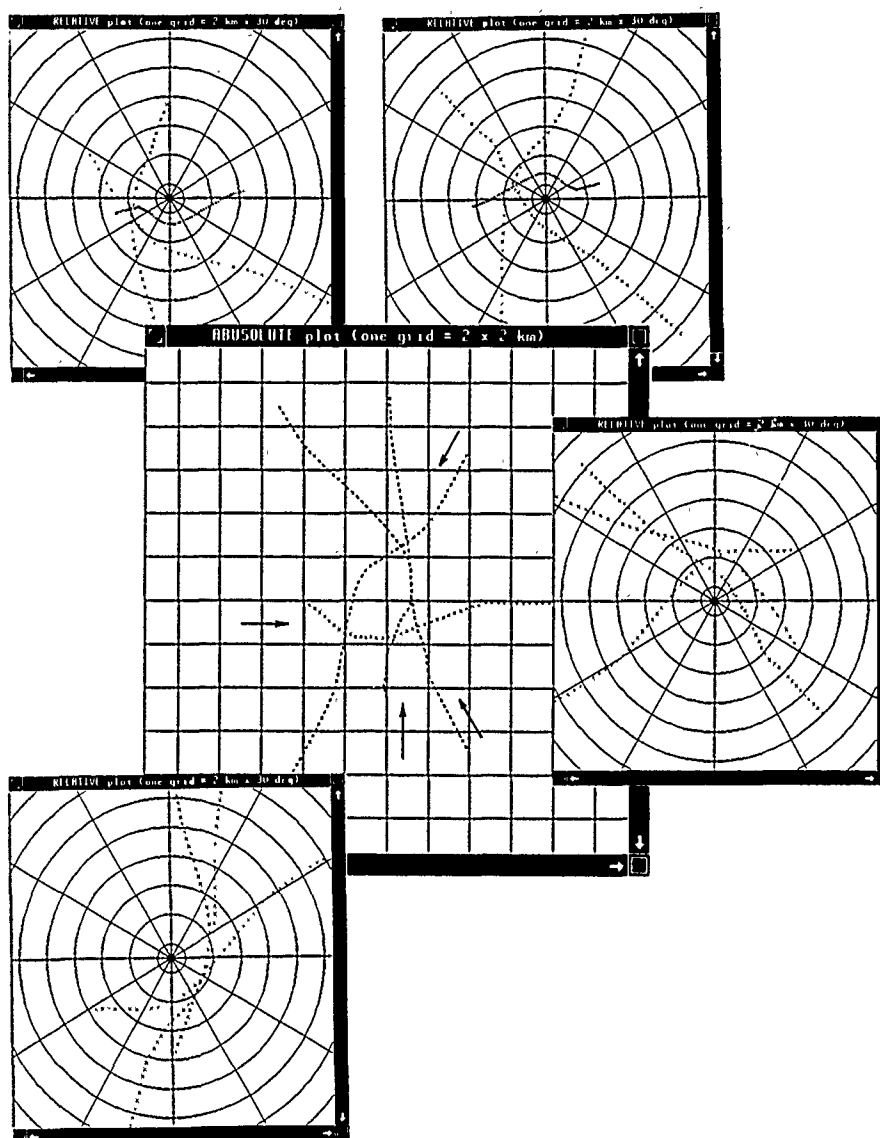


Figure 3. An example of four-ship encounter at the origin by SAFES.

Table 2. Principal particulars of type ships used for simulation.

Item	999GT-type Ship	499GT-type Ship
$L_{PP}$ (m)	75.0	62.0
$B_m$ (m)	12.7	10.0
$d_m$ (m)	4.9	4.17
trim(m)	1.0	0.0
$C_B$	0.72	0.70

#### 4.1 Assessment of a narrow waterway design

*Inland Sea* area of Japan (cf. Figure 4) is the important route for product carriers including chemical tankers and car carriers. This area is also very important fishing field. At the same time, it is also famous for its beautiful scenery with many small islands and nowadays there are already many long bridges and plans connecting the main island to small islands or even to *Shikoku* island.

The small islands prevent the straight waterway configuration nor enough sectional area in both width and depth. Besides, there are normally strong current and in spring sometimes heavy fog. So, there happens frequent casualties. Especially, *Kurushima Straits* is notorious for its narrow and poor outlook with strong current of 8 knots maximum. Of course, various countermeasures are provided such as a unique regulation "to sail west lane when the current is coming and to sail middle lane when the current is going" as well as a current signal, but growing of sea traffic makes some unfortunate encounters of ships.

So, the next countermeasure is planned to construct a bypass waterway for smaller vessels to reduce the main traffic. However, this bypass itself is still narrow and bent as roughly shown in Figure 5 with strong current and several rocks. Therefore this route called *Miyanokubo Straits* was naturally used only by local fishermen or local cargo shipmasters. The plan is to consolidate the waterway to allow sailing up to 1,000GT vessels with navigational aids and dredging, if necessary.

**Simulation conditions.** In a committee to assess the safety and to plan the waterway configuration, the author has carried out the simulation using **SAFES** for some alternative waterway designs. The simulation was done concerning to the following items using a 999GT-type cargo ship and a 499GT-type cargo ship whose particulars are shown in Table 2.

- Is proposing two-way traffic route using *Funaore Strait*\* as shown in Figure 6 safe for a 1,000GT cargo ship meeting with a 500GT cargo ship? Here, the problems are as follows.

\* *Funa-ore* is read *Ship-broken* in Japanese.

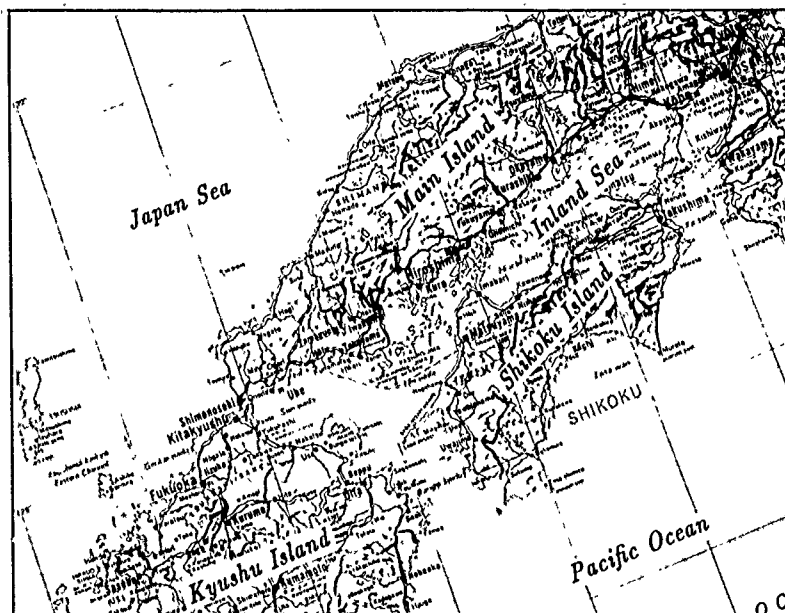


Figure 4. *Inland Sea* area of Japan.  
(from *Britanica International Atlas*)

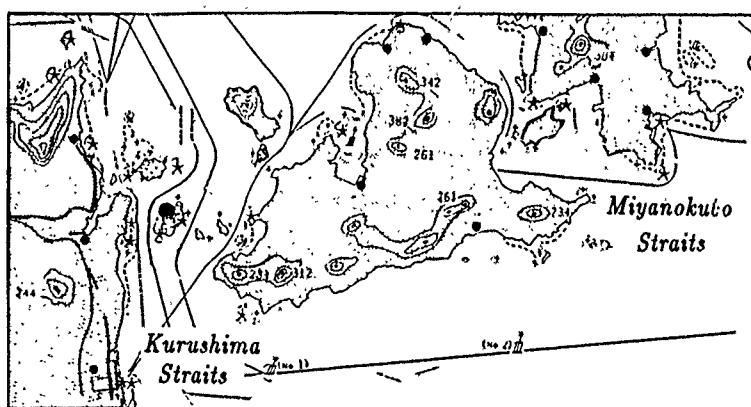


Figure 5. *Kurushima Straits* and its bypass *Miyanokubo Straits*.



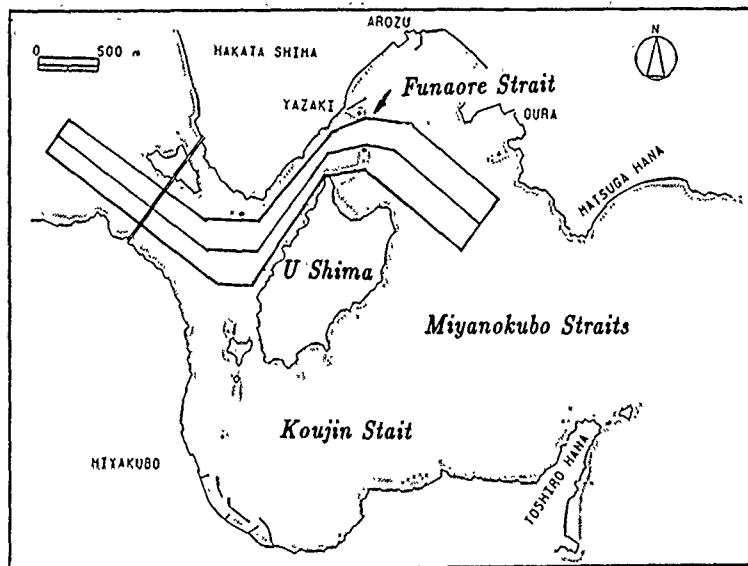


Figure 6. A proposed two-way traffic route set in *Funaore Strait* of *Miyanakubo Straits*.

- The width at the most narrow part of the waterway is only 160 m, where the curvature of the waterway is also worst.
- Several rocks and a local harbour area are adjacent, so it is very difficult to widen the curved area.
- The strong current exists and islands prevent long-distant view.
- If the answer of the above question is no, is it possible to propose any one-way separated traffic route using *Koujin Strait*<sup>1</sup> west- and southward of an Island *U Shima*? In this case, still the following points should be considered.
  - There are many rocks in the westward of *U Shima*.
  - The southward of *U Shima* is especially a nice fishing field.

**b. Current effect.** As for the mathematical model of ship motion in non-uniform current and estimation of its derivatives etc., several models and methods are already proposed (cf. Appendix), and it seems to be necessary to simulate the current effect. Indeed, according to the *questionnaire* carried out to investigate the traffic problems in *Miyanakubo*

<sup>1</sup> *Miyanakubo Straits* are the generic name including *Funaore Strait* and *Koujin Strait*.

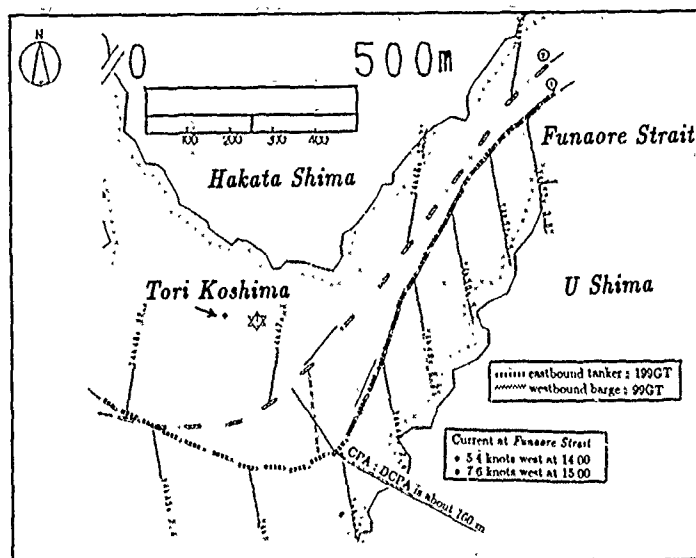


Figure 7. An example of actual ships' path in Funaore Strait.

*Straits*[8], 14.3 % of repliers of shipmasters pointed out the strong current is one of the navigational difficulties in this area. Therefore, in most cases except the cases where the arrival time is rigid, shipmasters answered that they operate their ships when the current is same direction with their ships' direction or weak enough not to be affected.

In the actual ship path investigation using a fixed radar on land[8], we cannot find significant effects by current, although the investigation was carried out at nearly the strongest current. Figure 7 is one of the exceptional cases in which we can imagine there was slight current effects on the eastbound tanker. This may mean that the current effect itself is very big, but that each helmsman compensates its effect within his control loop. We can find the interesting results in the simulator study carried out for *Kurushima Straits*[9] concerning to the human ability of compensating the current effect and its effect during the simulator experiments for various types of ships with different stability. The author would like to point out that in the fast-time simulation we *may* ignore the current effect to some extent and regard it as relative ship speed. Of course, in ship handling simulator experiments, we cannot neglect the non-uniform current dynamics and the current effect in fast-time simulation should be carefully investigated in the future work.

Furthermore, in this case, no detail data of captive model tests etc. is available and the considering ships are rather small. So, as a first step of research, Nomoto's so-called K-T

model[10] was used for each ship's motion, while the coefficients were estimated through the procedure describe in **Appendix**. The water depth is assumed to be dredged constant of 7.35 m throughout the waterway. No bank effect nor approaching ship's interaction is considered. As for the current and the constant wind will be planed to be implemented in the mathematical model, though they are neglected here.

**c. Validation of the simulation.** It is necessary to check if the simulation results are creditable or not. Validation itself is rather difficult, but here rough validation was done to tune the navigator's model so as to navigate successful in the given waterway. Figure 8 is one of the validation result where westbound 999GT-type ship and eastbound 499GT-type ship are designed to sail at the centerline of the waterway to meet at the west part of the waterway. The number of "course changing points" given to each ship's "modelled navigator" is around 5~8. Each ship-mark is the real size and direction and plotted every 1 minute. The long arrows show each ship's sailing direction and the small numbers aside the ship-marks indicate the time from the simulation start time. The bidirectional arrow connecting each ship is the DCPA (Distance of the Closest Point of Approach). Each grid is plotted every 0.5 km and the proposed waterway boundary is indicated by two polygons as shown in the figure.

Each ship could sail fairly smooth to trace the centerline of the waterway, and successfully avoid a collision at around 22 mintues. Ship speed is 5 knots each. In this case, the eastbound ship sailed too close to the waterway boundary there, but in the actual navigation both ships will sail right-hand side of the waterway as shown in the following figures. So the basic features of SAFES can be regarded to be applicable to such a waterway navigation.

**d. Evaluation of two-way traffic.** Various situations in this route will be discussed by simulation results. Figure 9 is the same case with Figure 8, but each ship is sailing in right-hand part of the waterway (case 1.2). In this case the westbound ship slightly avoided at around 22 minutes and both ships could pass the waterway safely. Following two cases show the effect of meeting place. All the conditions except the meeting place are same with case 1.2. In Figure 10 (case 1.3) both ships could pass in the narrowest part of the waterway, but there are not enough distance between the boundary. In Figure 11 (case 1.4), where the condition is more severer, it is rather difficult to keep safe distance between the boundary and the eastbound ship overturned after the collision avoidance.

The following two cases are the same with case 1.3 except the ships' speed. In Figure 12 (case 1.3U6) the speed of both ships is set 6 knots and in Figure 13 (case 1.3U7) it is set 7 knots. The faster the ship speed is, the greater is the degree of the overturn. One of the reason for this is the reasoning interval. In the system SAFES ship motion calculation is carried out every 1 second, but the navigator model judges and take orders every 10 seconds. We should change the reasoning interval according to the size of the ship or the ship speed. Several other simulations with different conditions were also carried out, and the author has concluded that there may happen dangerous cases, if this route will be allowed two-way traffic.

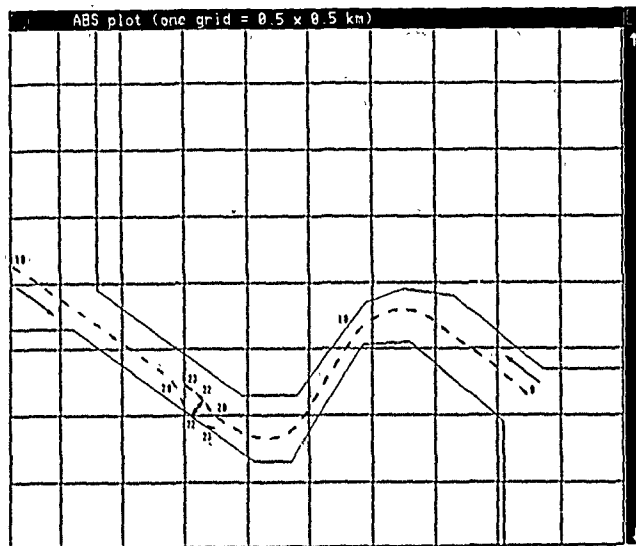


Figure 8. Two-way traffic route (case 1.1).

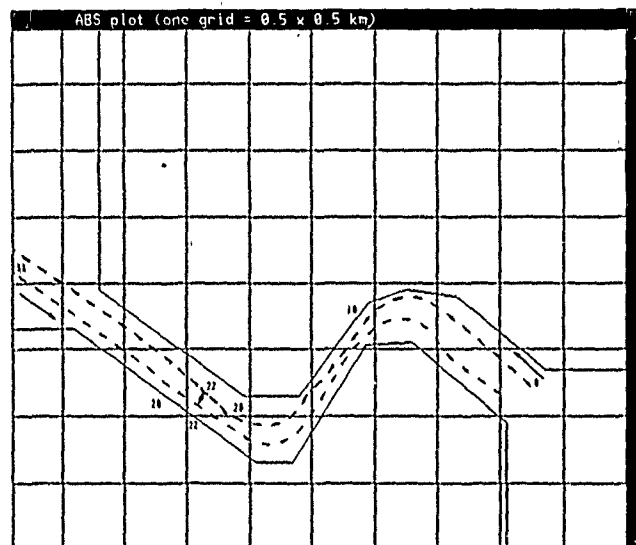
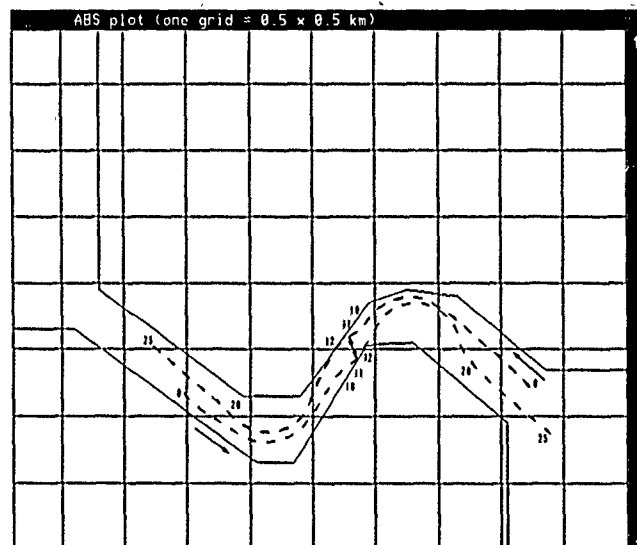
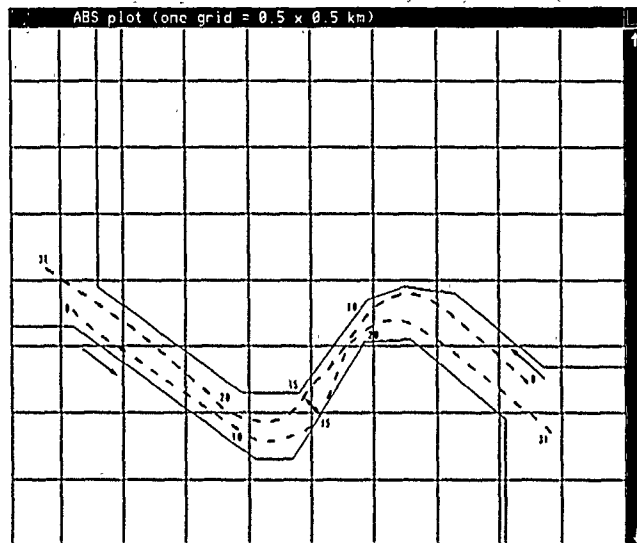


Figure 9. Simulation result of two-way traffic route (case 1.2).



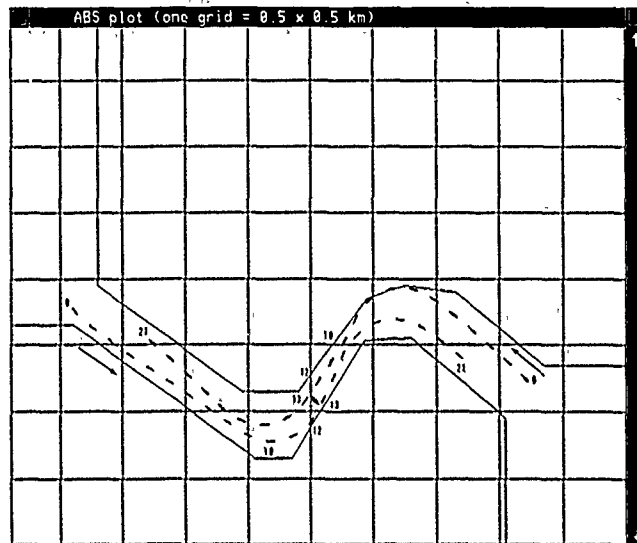


Figure 12. Simulation result of two-way traffic route (case 1.3U6).

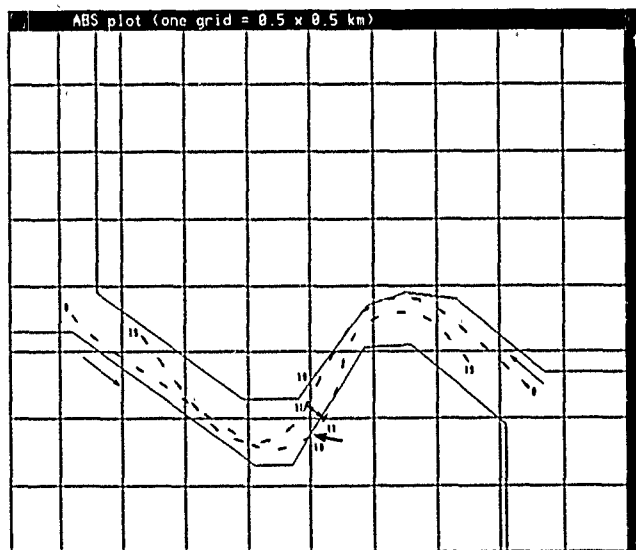


Figure 13. Simulation result of two-way traffic route (case 1.3U7).

**e. Evaluation of one-way traffic.** Next, one-way separated waterway was evaluated using SAFES. In this waterway, the westbound ships will sail north part of the route and the eastbound ships will sail from west part to the south part of the separated route. It is verified in the previous one-way traffic simulation that in the west part of the route, it is not so difficult to sail safely, even if two ships will meet there. So, in this section the following two points will be checked.

- Is it possible to turn 90 degrees at the southern route?
- Is it possible to permit overtaking actions for both routes?

In Figure 14 (case 2.1), the former point is checked. In the figure the westbound ship is the 999GT-type ship at 5 knots and the eastbound ship is the 499GT-type ship at 5 knots. In the following two figures, the latter point is checked. In Figure 15 (case 2.2), the 999GT-type ship at 5 knots will be overtaken by the 499GT-type ship at 6 knots in the westbound and the 499GT-type ship at 5 knots will be overtaken by a 199GT-type ship<sup>†</sup> at 7 knots. Figure 16 (case 2.3) is the same condition with Figure 15 except that the overtaking places are more severe. In the case of Figure 16, both overtakings are quite dangerous. The near-miss point or out-of-bound point are indicated by short arrows. Of course, the actual pilots may navigate safely even in these cases, but these simulation shows the possibility of the casualties and they can be used to evaluate the waterway configuration.

#### **4.2 Marine traffic evaluation**

There is already a method to evaluate marine traffic statistically, which is so-called macro or network simulation[11]. This method is an application of queueing theory and can evaluate the traffic from quantitative aspect, so it is widely used for various projects designing or assessing waterways in Japan.

However, it cannot deal with precise manoeuvring properties of each ship according to each navigator's behaviours such as collision avoidance manoeuvres. Micro simulation[12] is thus proposed to fill these features into macro simulation. The author has also applied SAFES to micro simulation of a #-shape waterway[7]. Figure 17 is an example of the result of this simulation, where over 600 vessels with statistical speed, size and manoeuvring properties distributions were generated at statistical interval of arrival time in 24 hours. We can roughly evaluate the navigational safety by analyzing the results.

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<sup>†</sup>The particular of this ship is  $L_{PP} \times B_m \times d_m = 50.0 \times 10.0 \times 6.0$  (m).

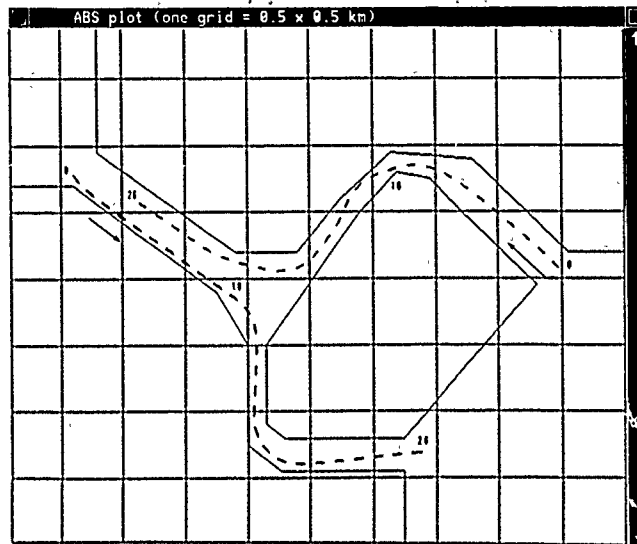


Figure 14. Simulation result of one-way traffic route (case 2.1).

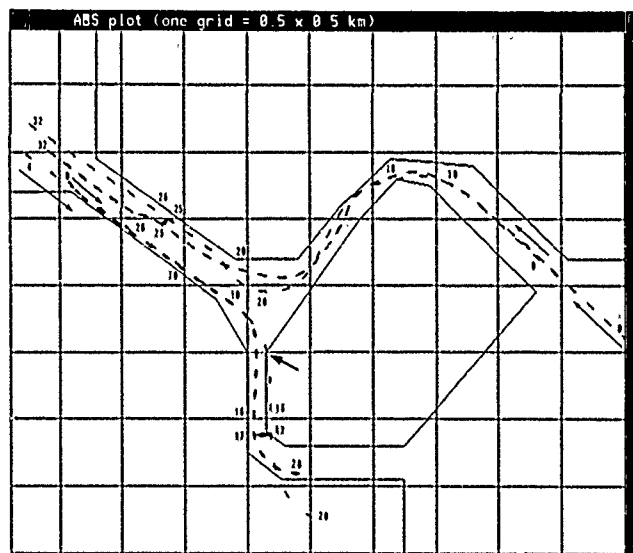


Figure 15. Simulation result of one-way traffic route (case 2.2).



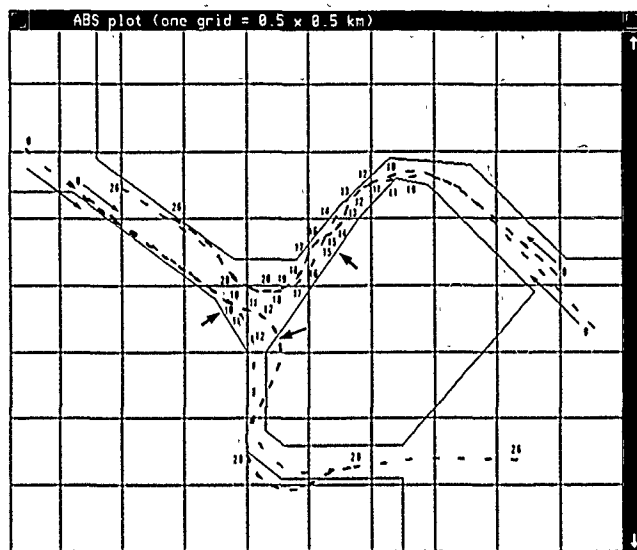


Figure 16. Simulation result of one-way traffic route (case 2.3).

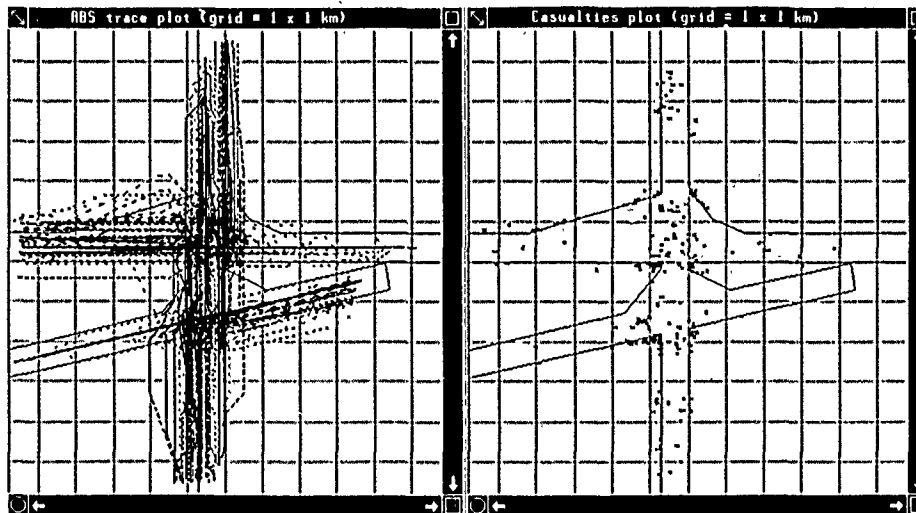


Figure 17. An example of marine traffic simulation using SAFES.

## 5. CONCLUDING REMARKS

In this paper, a method of modelling of a navigator and its integration to a fast-time simulation method **SAFES** are introduced and the validity of these methods are shown through two actual applications. There still remain many problems to be solved, and the author would like to further investigate this methodology for more practical applications especially for the waterways design.

The main conclusions obtained through this research are summerized as follows.

- The model of a navigator combining fuzzy theory and expert system is useful for integrating into a fast-time simulation system.
- The fast-time simulation system called **SAFES** is effective for various applications, especially for assessment of narrow and congested waterways.

The following points should be further improved to make the system more reliable and useful.

- The mathematical model of ship motions for various environmental conditions
- Constructing more reliable knowledge base including more natural and common-sense knowledge
- Improving the structure of knowledge base for reducing reasoning and judging time
- Easy handling for setting the simulation parameters
- Establishing statistic data acquisition and qantitative analysis system

## ACKNOWLEDGEMENTS

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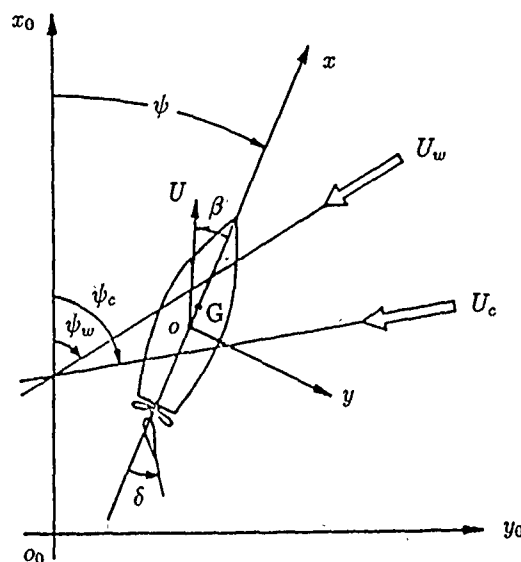


Figure 18. Coordinate system.

## APPENDIX MATHEMATICAL MODEL OF SHIP MOTIONS

### A.1 Model of ship motions in non-uniform current

The equations of ship motions in non-uniform current[A.1] may be expressed as follows according to the coordinate system shown in Figure 18.

$$\begin{aligned} (m + m_y)\ddot{u} = & (m + m_y - X_{vr})v_a r + (m x_G + X_{rr})r^2 \\ & + X_{vv}\dot{v}^2 - (m + m_y)U_c r \sin(\psi_c - \psi) \\ & + (1 - t)T - R_s - (1 - t_R)F_N \sin \delta + X_w \end{aligned} \quad (1)$$

$$\begin{aligned} (m + m_y)\dot{v} - (Y_{\dot{r}} - m x_G)\dot{r} = & Y_v v_a + (Y_r - m u_a)r \\ & + Y_{NL}(v_a, r) + (m + m_y)U_c r \cos(\psi_c - \psi) \\ & - (1 + a_H)F_N \cos \delta + Y_w \end{aligned} \quad (2)$$

$$\begin{aligned} (I_z + m x_G^2 + J_z)\dot{r} - (N_{\dot{v}} - m x_G)\dot{v} = & N_v v_a + (N_r - m x_G u_a)r \\ & + N_{NL}(v_a, r) + (m x_G - N_{\dot{v}})U_c r \cos(\psi_c - \psi) \\ & - (x_R + a_H x_H)F_N \cos \delta + N_w \end{aligned} \quad (3)$$

where

$m$  : mass of a ship

$m_x$  : longitudinal added mass of a ship  
 $m_y$  : transverse added mass of a ship  
 $I_z$  : moment of inertia around  $z$ -axis of a ship  
 $J_z$  : added moment of inertia around  $z$ -axis of a ship  
 $r$  : rate of turn around  $z$ -axis of a ship  
 $x_G$  :  $x$ -ordinate of center of gravity of a ship  
 $F_N$  : nominal force acting on a rudder  
 $X_w$  : longitudinal force acting on a ship by wind  
 $Y_w$  : transverse force acting on a ship by wind  
 $N_w$  : moment around  $z$ -axis acting on a ship by wind  
 $u_a, v_a$  : longitudinal and transverse relative flow velocities by current and can be expressed as

$$u_a = u + U_c \cos(\psi_0 - \psi) \quad (4)$$

$$v_a = v + U_c \sin(\psi_0 - \psi) \quad (5)$$

$u$  : longitudinal component of ship velocity  $U$   
 $v$  : transverse component of ship velocity  $U$   
 $U_c$  : current velocity  
 $Y_{NL}, N_{NL}$  : nonlinear hydrodynamic force (transverse) and moment (around  $z$ -axis) and they can be expressed as follows using cross-flow model.

$$Y_{NL}/\frac{\rho}{2}U_a^2Ld \equiv Y'_{NL} = -C_D \int_{-1/2}^{1/2} |v'_a + \xi r'| (v'_a + \xi r') d\xi \quad (6)$$

$$N_{NL}/\frac{\rho}{2}U_a^2L^2d \equiv N'_{NL} = -C_D \int_{-1/2}^{1/2} |v'_a + \xi r'| (v'_a + \xi r') \xi d\xi \quad (7)$$

where  
 $C_D$ : cross-flow drag coefficient

$$v'_a = v_a/U_a \quad (8)$$

$$r' = rL/U_a \quad (9)$$

$$\xi = x/L \quad (10)$$

$$U_a = \sqrt{u_a^2 + v_a^2} \quad (11)$$

## A.2 Estimation of derivatives

If data of captive model tests etc. are not available, following formulae are useful to estimate the derivatives.

**a. Linear derivatives.** Inoue *et al.* have derived the following semi-empirical formulae[A.2].

$$Y'_v = -(\frac{\pi}{2}\Lambda + 1.4C_B\frac{B}{L})(1 + \frac{2}{3}\frac{\tau}{d_m}) \quad (12)$$

$$Y'_r = \frac{\pi}{4}\Lambda(1 + 0.80\frac{\tau}{d_m}) \quad (13)$$

$$N'_v = -\Lambda(1 - \frac{0.27}{l_\beta}\frac{\tau}{d_m}) \quad (14)$$

$$N'_r = -(0.54\Lambda - \Lambda^2)(1 + 0.30\frac{\tau}{d_m}) \quad (15)$$

where  
 $\tau$  : trim  
 and

$$\Lambda = \frac{2d_m}{L} \quad (16)$$

$$l_\beta = \Lambda/(-\pi\Lambda + 1.4C_B\frac{B}{L}) \quad (17)$$

**b. Added mass and added moment of inertia.** Motora's charts[A.3] are very reliable, but here it is convenient to use the regression forms proposed by Clarke *et al.*[A.4].

$$m_v/\frac{\rho}{2}L^2d \equiv m'_v = \pi\frac{d}{L}\{1 + 0.16C_B\frac{B}{d} - 5.1(\frac{B}{L})^2\} \quad (18)$$

$$J_z/\frac{\rho}{2}L^4d \equiv J'_z = \pi\frac{d}{L}\{\frac{1}{12} + 0.017C_B\frac{B}{d} - 0.33\frac{B}{L}\} \quad (19)$$

$$Y_r/\frac{\rho}{2}L^3d \equiv Y'_r = -\pi\frac{d}{L}\{0.67\frac{B}{L} - 0.033(\frac{B}{d})^2\} \quad (20)$$

$$N_v/\frac{\rho}{2}L^3d \equiv N'_v = -\pi\frac{d}{L}\{1.1\frac{B}{L} - 0.041\frac{B}{d}\} \quad (21)$$

**c. Nonlinear derivatives and cross-flow drag coefficient.** Inoue *et al.* have also proposed the charts for them[A.2] and Kijima *et al.* have obtained the regression forms of them[A.5].

Cross-flow drag coefficient can be assumed as

$$C_D = -Y'_{vv} \quad (22)$$

**d. Rudder coefficients.** If data of rudder is available, so-called MMG's model[A.6] procedure to estimate normal rudder force coefficient, effective rudder inflow velocity and

angle is usable. In this paper, rudder force coefficient  $Y'_\delta$  and rudder moment coefficient  $N'_\delta$  were estimated to coincide with tactical diameter at rudder angle of 35 deg  $D_{T35}$ .

**e. Manoeuvrability indices.** Coefficients of Nomoto's 2nd order model[10], which can be written as follows, can be estimated using the above derivatives.

$$T'_1 T'_2 \ddot{r} + (T'_1 + T'_2) \dot{r} + r = K' \delta + K' T'_3 \dot{\delta} \quad (23)$$

where

$$T'_1 T'_2 = (m' + m'_y)(I'_z + J'_z)/D \quad (24)$$

$$T'_1 + T'_2 = \{-(m' + m'_y)N'_r - Y'_v(I'_z + J'_z)\}/D \quad (25)$$

$$K' = (N'_v Y'_\delta - N'_\delta Y'_v)/D \quad (26)$$

$$T'_3 = (m' + m'_y)N'_\delta/(N'_v Y'_\delta - N'_\delta Y'_v) \quad (27)$$

where

$D$  : stability criterion

$$D = Y'_v N'_r + N'_v(m' + m'_x - Y'_r) \quad (28)$$

If the ship is stable ( $D > 0$ ) and not so big, it can be more simplified into so-called Nomoto's K-T model[10] as

$$T' \dot{r} + r = K' \delta \quad (29)$$

$$T' = T'_1 + T'_2 - T'_3 \quad (30)$$

Dynamics of a steering gear is well modeled by the following equations.

$$T_E \dot{\delta} + \delta = \delta^* \quad (31)$$

$$\dot{\delta} \leq \dot{\delta}_{\max} \quad (32)$$

where

$T_E$  : time constant of a steering gear (sec)

$\dot{\delta}_{\max}$  : maximum rudder speed (deg/sec)

$\delta^*$  : rudder command

In this study,  $T_E$  is set 2.5 sec. and  $\dot{\delta}_{\max}$  is set 3.5 deg/sec.

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## GLASS CONTROLS FOR A GLASS SHIP

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### ABSTRACT

The Osprey Class Minehunter - MHC-51, is a glass reinforced plastic (GRP) ship based on the Italian Lerici design. The machinery/ship control system (M/SCS) is also a new design that uses "glass" as the basis for man-machine interface to the control and monitoring of the ship.

The M/SCS operator's consoles have followed the road of the combat system designer and integrated the cathode ray tube (CRT) into a fully distributed microprocessor based machinery control system. The "glass console" is used by the operator as a window on the machinery plant data base; all input commands are initiated through the CRT and all plant data is displayed by the CRT.

The MHC-51 has a unique link between the combat system and the machinery control system. This electronic communications link permits the passing of minehunting critical information to facilitate the role of the helmsman and machinery watchkeeper. Integration of the data from

these two critical ship systems is a step into the future in terms of the use of more computer automation to ease the traditional workload of the watchkeepers.

This paper describes the MHC-51 machinery/ship control system and its interface to the combat system, with a focus on the use of the "glass console" as a replacement for the conventional instrumentation that has traditionally been a way of life in the USN.

### INTRODUCTION

The concept of a machinery control system is not new, dating back to the early days of iron men and wooden ships. In those early days, machinery control was carried out through a relatively simple communication protocol; as the beat of the drum was heard, the oar was expected to make a positive stroke. The speed of the vessel was controlled by the frequency of the drum beat, with a little encouragement from the whip.

As warships moved from sail to more sophisticated prime movers, control requirements increased in complexity. However, machinery control system development has not kept pace with the technological developments of related fields, such as in the power generation and process control industries. In the process control industries, developments have taken place in two basic categories: the man-machine interface, and the architecture. In the past decade, the marine control technologies used in the USN have progressed from the traditional point-to-point, hard wired systems, to systems that use the data bus for monitoring signals while retaining point-to-point connections for all control signals, and finally to systems where the data bus is used for all control signals and all monitoring signals.

Further to the architecture changes, the man-machine interface (MMI) design has remained traditional in the USN, relying on digital panel meters, analog meters, and a multitude of push-buttons and lights as indicated by the MCM-1 control system. This has been modified to some extent in the DDG-51 with the introduction of the plasma display. However, in the 1980s, the introduction of the "glass cockpit" into both military and civilian aircraft, along with the fly-by-wire control systems, prompted the USN to move its control and

monitoring requirements forward in technology. The direction provided in the MHC-51 is a fully integrated system that utilizes the data bus for all communications and the CRT as the main man-machine interface in the "glass control room."

#### MHC-51

The Osprey Class Minehunter, MHC-51, is a glass reinforced plastic (GRP) ship based upon the Italian Lerici design, with particulars as follows:

- o length overall 57.25 meters
- o beam 10.95 meters
- o draft 2.86 meters
- o tonnage 880 metric tons

The MHC-51 has a unique propulsion system when compared to other USN warships. The diesel propulsion plant drives two Voith-Schneider propellers that provide directional thrust to enable the ship to move and to control the direction of the movement. This highly maneuverable propulsion system is a major requirement for minehunting vessels.

#### MACHINERY/SHIP CONTROL SYSTEM

To provide the Commanding Officer with the optimum use of this unique propulsion system in relation to the

combat requirements, a unique machinery/ship control system (M/SCS) was introduced. One of the requirements of the MHC was to provide control and monitoring capabilities from the pilot house, the combat information center (CIC), the central control station (CCS), and the local control panels (LCP).

To comply with this requirement, and to minimize the amount of weight and space occupied by the M/SCS, the system utilizes a triplicated serial data bus for all control and monitoring communication signals. The data bus permits the control and monitoring functions to be carried out from the first three locations described above, with the local control panels being used as a fall-back position. In addition, mechanical devices are provided in the machinery spaces to enable control of the prime movers.

With introduction of the serial data bus came requirements for a fully distributed system based upon use of independent microprocessors. The MHC-51 has three data acquisition units (DAUs). These DAUs not only acquire data, but also act as smart controllers to all of the machinery in their locale. The introduction of the control requirement to the DAU is a jump forward taken by the MHC-51.

To round out the major elements of the system, the "glass" console concept was introduced to provide all of the control and monitoring requirements. This console utilizes a CRT as the man-machine interface (MMI). Through the MMI, the operator institutes all control and receives all monitoring signals from the machinery plant. As shown in Figure 1, the pilot house, the CIC, and the CCS all have consoles that utilize this man-machine interface. The introduction of this type of MMI provides the USN with the ability to link the machinery control system with the combat requirements for accurate navigation in the prosecution of mines. The data required for this process is produced by the navigation system and sent electronically to the M/SCS, where it is acted upon to keep the vessel on track or on station in relation to the mine.



reception only a single cable at any one time. In a mode transparent to the operator, the receiver cable is changed every five minutes to provide the operator with confidence in the operational availability of the system. At any time, the operator can call up a page on the CRT and see which of the data bus cables and subsystems are on-line or off-line. This page is shown in Figure 2.

03-7M1-1500 DACBUS-M STATUS PAGE 00:30:10									
Pilot House MC 1		DAU 1	DAU 2	DAU 3	DCPU	NCCS			
LINE		UP	UP	UP	UP	UP			
Main MC 2		DAU 1	DAU 2	DAU 3	DCPU	NCCS			
LINE		UP	UP	UP	UP	UP			
STATION STATE		DAU 1	DAU 2	DAU 3	DCPU	NCCS			
		UP	UP	UP	UP	UP			
TDC 01		SCCP	SCCP	AC 01	AC 02	TDC 01	TDC 02		
		UP	UP	UP	DOWN	MASTER	SLAVE		
FILE	RESULTS	SETPOINT	DEVIATION	RTIC	RTIC	RTIC	RTIC	RTIC	RTIC
		PAGES	PAGES	CALCULATED	STATUS	STATUS	STATUS	STATUS	STATUS

Figure 2. DACBUS-M Status Page  
MACHINERY CONTROLLERS (MC)

The machinery controllers are software-driven with INTEL 80186 processors. Two controllers are provided for redundancy, one on the Pilot House Console and a second one on the Main Control Console. They operate in a redundant mode, one master, and one hot standby, and provide the following functions:

control of information transfer to and from all subsystems connected to the data bus

- o all automatic control actions from pre-defined control algorithms, including:
  - coordination of engine start-up and shut-down
  - automatic sequence control of all ancillary and auxiliary machinery;
  - steering control.

Both master machinery controller and the standby controller perform all computations. In the event of failure of the master controller, the standby controller assumes control and the operator is made aware of the problem through an error message on his CRT. On a regular schedule, the master and standby controllers change jobs to provide the operator with confidence in system availability. The swapping of jobs by the controllers is done only when the plant is in a steady state condition.

The machinery controller polls all sensors, actuators, and man-machine interfaces three times per second to ensure that an alarm or warning can be annunciated to the operator within one second of its occurrence. Should both machinery controllers

fail, one of the consoles will automatically take over the bus communication functions.

#### **DATA ACQUISITION UNITS**

The DAUs provide the connection points between the control and monitoring system and the sensors/actuators in the ship. Since each DAU contains its own INTEL 80186 microprocessor, the intelligence of the system is distributed throughout the ship to permit redundant control inputs for critical machinery. The DAU functions include:

- o acquisition of plant I/O information
- o comparison of readings for change
- o comparison of readings against limits
- o checks on readings for reasonability
- o issue of actuator commands.

All high speed closed loop control is conducted by the DAU, with the results passed to the data bus for dissemination to the other subsystems. A typical example of this is the closed loop control requirements of the Voith-Schneider propeller actuators.

In a typical configuration, the DAU handles

about 300 signals, of which 60 are digital and the remainder are analog. This configuration provides an additional 20 percent in spare capacity to accommodate system growth.

#### **PERIPHERAL DEVICES**

BELL/DATA LOGGER. The system includes two militarized bell/data loggers. The data loggers print the alarms, warnings, errors, and bells as they occur.

#### **MAN-MACHINE INTERFACE**

Each MMI in the CCS, Pilot House, and CIC consists of one high resolution color video display unit. In the MHC-51, a computer is placed between the system operators and the machinery plant. The watchkeeper no longer has to scan a large console of dials and gauges; instead his video display unit acts as a window into a large array of data. This effectively relieves the operator of the requirement to rely on his long term memory in relating new data to the applicable system. Instead of having to scan a plethora of gauges to maintain a mental picture of the plant, the M/SCS now presents data on demand. Video display units

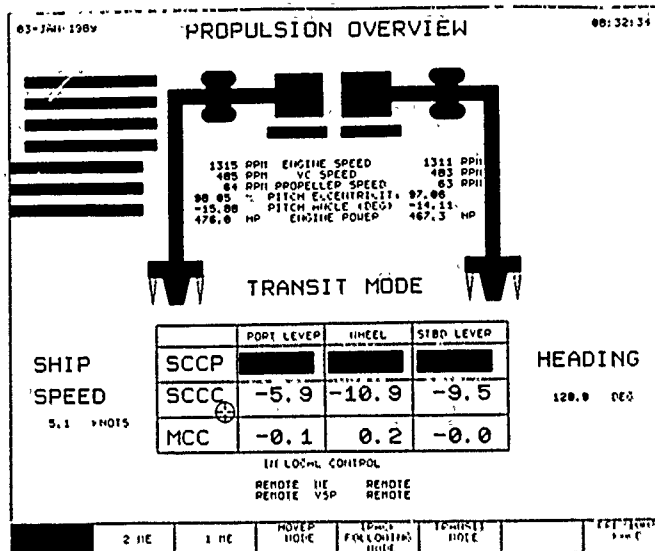


Figure 3. Propulsion Overview Page

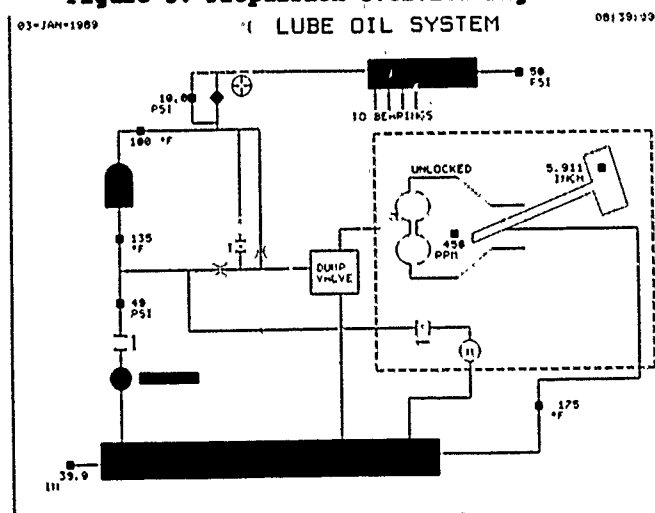


Figure 4. Fluid variator & Gearbox Lube Oil System

provide, in a structured format, all information needed by the operator at any time. Desired information can be acquired by simply pressing the appropriate key. The

information will be displayed within one half second of the demand. Examples of this type of information are shown in Figures 3 and 4.

#### CONTROL CONSOLES

Control consoles are configured such that each single bay can contain a single 19-inch militarized color CRT. The main features of the glass control room consoles are the CRT screens, a track ball, function keys, throttles, a ship's wheel, keypad, and audible alarm indicators. The track ball and function keys are used to display pages on the screens and execute control functions. The throttles and wheel provide the capability to enter ship speed and course demands. Figure 5 depicts the Pilot House console.

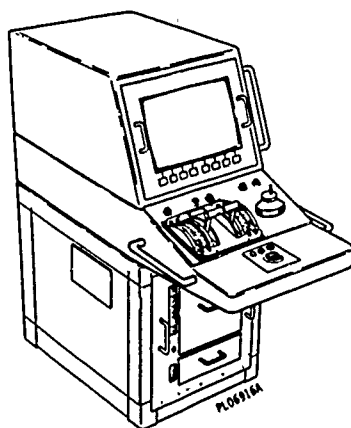


Figure 5. Pilot House Console

**SHIP CONTROL CONSOLE -  
PILOT HOUSE (SCCP).**

The SCCP is capable of shaftline power control, including the ability to change the state of engines from off-line to on-line through an automatic control

sequence. The SCCP also provides the CRT pages required to perform the trackkeeping and position-keeping required to perform the minehunting role. Damage control information is also provided on the CRT as information to bridge personnel.

**MAIN CONTROL CONSOLE  
(MCCS).**

The MCCS provides the MMI features required for the operator to carry out all control and monitoring functions for the propulsion machinery systems. Additionally, the MCCS can also perform ship control and monitoring functions, including steering, damage control, and electrical system functions.

**MAIN CONTROL CONSOLE PORT  
(MCCP).**

The MCCP provides the capability to manage the damage control and electric plant functions. Additionally, the MCCP can call up all of the data related to the propulsion functions, and can operate the propulsion plant (e.g., start engines), but he cannot control thrust, because this console does not contain a set of



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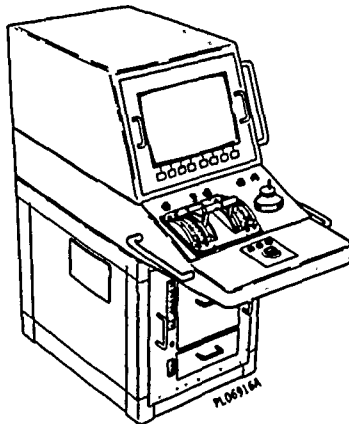


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throttles and a wheel. The M/SCS diagnostic maintenance functions are also performed from this console.

#### **DAMAGE CONTROL PANEL (DCP).**

In addition to use of the CRT as the main man-machine interface, there is a requirement for the system to contain a traditional damage control panel. This panel provides the alarm information related to the fire, smoke, and flooding requirements of the ship. This information is processed by a separate processor, that is part of the damage control panel. Information from this processor is passed to the main system through a communication link, and the information is available on all CRT displays.

#### **UNINTERRUPTIBLE POWER SUPPLIES (UPS).**

The entire M/SCS is powered with two 4-KVA uninterruptible power supplies. These units can provide power to the system for up to 30 minutes after a complete failure of the ship's electrical generation and distribution system.

#### **LOCAL CONTROL PANEL (LCP)**

The LCPs are provided as

backup to control the main propulsion prime movers and the electrical generators in case of system failure. The LCPs use conventional instrumentation and are not connected to the data bus. The basic emergency control and monitoring functions can be executed from the LCPs.

#### **NAVIGATION/COMMAND AND CONTROL (N/C<sup>2</sup>)**

The MHC-51 Combat System design is an advanced Integrated Combat System engineered specifically for the minehunter Coastal Osprey Class. The system makes use of previously developed MCM sensors, such as the AN/SQQ-32 Variable Depth Minehunting Sonar and the AN/SLQ-48 Mine Neutralization System. A critical component of this system is the Navigation/Command and Control (N/C<sup>2</sup>) System.

The N/C<sup>2</sup> consists of two display consoles, a storage/retrieval group, and a computer group. One of the displays is used for Command and Control, providing the Tactical Action Officer (TAO) with the tactical situation. The other display can be utilized as a Command and Control Station or Ship Control Station.

In the MHC-51, all tactical displays are identical. Our approach combines a Navigation/Command and Control Console and a Ship's Control Console into one. In contrast to other

minehunter designs, during minehunting operations the vessel steering control is performed from the CIC.

Both consoles provide tactical information in graphical and tabular form. Color is used to enhance the presentation and provide sufficient detail for quick assessment of the Tactical Situation. The display features electronic digital charts, mine warfare charts, NTDS contact symbology, radar target tracking, collision avoidance, sonar contact tracking, and an extensive mission planner.

#### **PRECISE POSITIONING**

The primary mission of the MHC-51 is to detect, identify, and destroy mines. This mission requires a precise positioning system to accurately position the vessel over the required tracks and maintain a safety margin. In addition, minehunters are required to hover at precise points while undertaking identification, classification and neutralization operations. All of this is performed at very low speeds and, in the case of the hover mode, the vessel is required to maintain its position considering the forces acting on the ship (e.g., wind, tide, waves). The problem is compounded by the fact that all these operations must be conducted while maintaining the lowest possible pressure, acoustic, and magnetic signatures. In the MHC-51, a variable depth

sonar is deployed during minehunting. This requires the lowest possible acoustic noise signature to optimize sonar operation.

During the design phase of the MHC-51, advanced simulation techniques were used to model the entire machinery/ship control system including the interfaces to the Combat System. Extensive use of simulations were used to develop the control algorithms necessary to control and monitor the machinery/propulsion plant. Further analysis and simulations were required to consider the effects of environment, use of propellers, engine RPM, and the operation of the fluid variators.

The result was a set of real time algorithms that consider the existing environmental conditions and the status of the machinery/propulsion plant to calculate the commands to the various controlling and governing devices. Ship's position is provided to the Integrated Positioning System via a triplicated data bus, allowing the Tactical Action Officer to have a direct impact on the position of the ship. The mine warfare officer, helmsman, and commanding officers are located in the CIC during minehunting operations and have direct control of the ship's navigation and positioning in both the trackkeeping and hovering

mode. As indicated earlier, the MHC-51 design provides for a dual-role console in the CIC room. This console is positioned next to the TAO station. The mission plan calls for the helmsman to be relocated to the CIC any time minehunting operations are conducted.

The Ship Control Console CIC (SCCC) provides the control devices necessary to control the diesel engines, fluid variators, and Voith-Schneider propellers.

#### **TOTAL INTEGRATION**

As indicated by the descriptions provided above, the MHC-51 M/SCS is a unique system that provides total integration of all platform functions required for the combat system to be effective. The system is not just a propulsion control system, it is an integrated platform management system that provides the following functions:

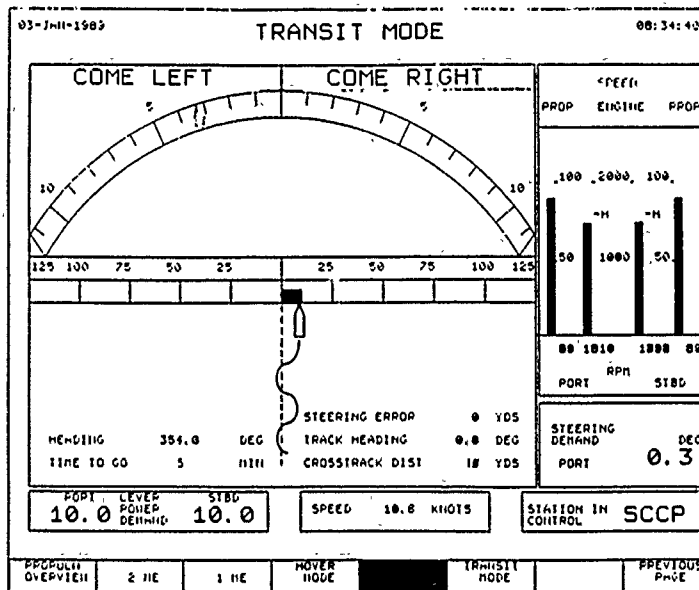
- o propulsion control and monitoring
- o ancillary machinery control and monitoring
- o auxiliary machinery control and monitoring
- o damage control and monitoring
- o electrical control

and monitoring

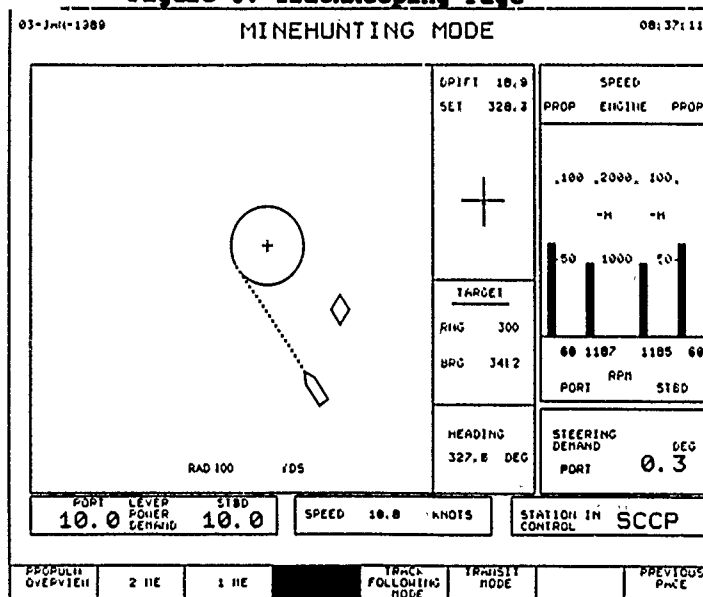
- o steering control and monitoring.

In addition to the platform functions, the M/SCS is linked electronically to the ship's navigation system through the Pilot House Console and the Combat Information Center Console. This link is the mechanism that permits the ship to maintain its track or to maneuver away from the mine during minehunting operations.

To perform the trackkeeping or hover functions, the M/SCS must be placed into the correct mode of operation. This is done by selection of the appropriate page at the console which is the station-in-control. Once selected, the process permits the operator to use the dynamic aspects of the page under display to keep the ship on course. Figure 6 displays the page associated with trackkeeping, and Figure 7 displays the page associated with hovering.



**Figure 6. Trackkeeping Page**



**Figure 7. Hovering Mode Page**

These two pages provide

the information required to steer the ship. The dynamic elements of the pages can be displayed for monitor or control purposes in the Pilot House, CIC, and CCS. The multifunctionality of the CRT based consoles provides the MHC-51 with the ability to drive the ship from any of the three positions without the need for the traditional secondary steering console.

#### **THE FUTURE**

The M/SCS for the first MHC-51 has been completed as described in this paper. The configuration of the MHC-51 lends itself to improvements as the in-service component of the life cycle commences. There are several areas where consideration can be given to providing further reductions to the operator's workload and, at the same time, provide an increase in platform capability. These areas include:

- a. **AUTOMATION.** The current degree of automation in the MHC-51 is limited by the traditional thought process in the original design, and the technology that was available at that time. All control functions in the M/SCS are software driven; therefore, any additions can be made through the addition of software into the existing processors.

Each processor has been sized to permit a 20 percent expansion in capability. As the operators of the MHC-51 become comfortable with the M/SCS, they will recognize that, through simple software modifications, their jobs can be made even easier.

- b. **TRAINING.** The design of the M/SCS lends itself to the introduction of the onboard embedded trainer concept. In short, this means taking a console off-line in software and using it as a trainer. This can be implemented today with the addition of one extra circuit card in the CCS console. In the event that the console under training is required for real plant operation, it can be reconfigured within 20 seconds.
- c. **MAN IN THE LOOP.** Currently there is a man in the loop in regard to trackkeeping and minehunting operational activity. The control system for these functions is in software, and the addition of a

software-based maneuvering autopilot would simplify the operating functions significantly.

- d. **NOISE.** A key area for consideration in the minehunting role is the reduction of ship's own noise, in particular, the noise generated by the propellers. It is recommended that consideration be given to a noise reduction loop that contains an active hydrophone in the circuit.

#### CONCLUSIONS

The MHC-51 machinery/ship control system is an evolutionary development in the field of total platform control. This evolution has taken place through the use of a modern control system architecture in combination with a man-machine interface that permits the display of all information essential to the operation of the ship. The electronic interface of the combat system with the machinery control system permits a direct response to the threat. The introduction of this technology into service in the USN will provide the Navy with a jump in systems technology, and it will permit subsequent enhancement of the system as the Navy becomes more familiar with the capabilities of the

technology.

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**THE MANEUVERING DESIGN WORKBOOK  
AN APPROACH TO CONTROLLABILITY DESIGN**

by

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The opinions expressed in this paper are those  
of the authors and do not necessarily reflect  
those of their employers.

**1. ABSTRACT**

Recent regulatory initiatives by IMO and USCG to improve ship handling safety will require the ship designer to take a closer look at ship controllability as an integral part of the overall design. To date there has generally been a lack of consistent controllability design techniques for the Naval Architect to employ in the design process. The Maneuvering Design Workbook has been developed by Society of Naval Architects and Marine Engineers (SNAME) Panel H-10 (Ship Controllability) to draw together available references and tools used in ship controllability design and present a congruous process for integrating them in the design cycle. The development of the Design Workbook was initiated by the 1983 SNAME Annual Meeting paper titled "Design and Verification for Adequate Ship Maneuverability". Numerous authors have contributed their technical expertise to the project. The Maneuvering Design Workbook is intended to be used in conjunction with other technical references such as the revised Controllability Chapter of PNA. The Maneuvering Design Workbook is presented in a modular format which supports the design cycle process. Regulatory, Operational, and Technical view points are presented to define a balanced picture of the compromises needed in design trade-offs. Design modules present tools and rules of thumb for use in specific technical areas to aid in defining the controllability potential of a ship. Future directions in commercial and Naval ship design are discussed along with their impact on current maneuvering assessment techniques and applications for new technology.

**2. INTRODUCTION**

Controllability is the quality of the movement of a ship while maneuvering, and encompasses all aspects of determining a ship's dynamic trajectory, speed, and acceleration [1]. The 1983 Society of Naval Architects and Marine Engineers (SNAME) paper titled "Design and Verification for Adequate Ship Maneuverability" posed

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the question: "What constitutes a good maneuvering vessel?" and "How can adequate maneuverability be specified, designed for, and verified?" [2]. The Maneuvering Design Workbook presents an aid to the naval architect in the process of addressing this question.

SNAME Technical and Research Panel H-10 (Ship Controllability) under the hydrodynamics committee, has been working to develop and prepare the Maneuvering Design Workbook for publication. It represents a culmination of effort spanning several years. This paper summarizes the contributions of many authors who have provided their technical expertise to the project. This paper provides a review of the Maneuvering Design Workbook and discusses how it was developed, why it was developed, and how future trends in ship design will affect its use.

### 3. THE NEED FOR A DESIGN WORKBOOK

The need for maneuvering design tools has always existed. "The importance of being able to steer and maneuver a water craft must have been obvious even to prehistoric man" [3]. Ships should possess a minimum of basic control qualities to enable course keeping, turning, recovery from turns, operation at slow speeds, and stopping [2].

In the past, different rules of thumb and assessment techniques have been developed to aid the ship designer in developing ships having those basic qualities. However, many of these tools, if not proprietary, were widely dispersed throughout the technical literature. The naval architect who is not a maneuvering specialist usually does not have time to research a wide array of sources for guidance in estimating the maneuvering potential of his design concept. The task of integrating the study of maneuverability potential into the design process can become a significant portion of the project, taking valuable time from other areas of concern.

Traditionally, the design of a ship is based on a previous successful design or "parent" from which minor changes are made to satisfy new requirements. Thus the ship designer relies on experience gained from past practice to guide him in the application of maneuverability concepts to the new ship. This time-honored approach is reasonable provided the new design does not vary significantly in proportion, form, speed or hydrodynamic arrangement from the ship used as the reference.

The economic environment from which most commercial designs have evolved has changed significantly over the past decade. The naval architect is forced to examine an increasingly broad range of concepts to satisfy a set of specified goals including broadened regulatory obligations. Consequently, an appropriate parent design may not be available for reference. This has led to innocent

design compromises which have resulted in some commercial vessels delivered with inherent maneuvering capabilities which were unsuited for their particular areas of operation.

A well known incident has been frequently discussed as an example of the need for applying increased maneuvering design considerations during the design process. A series of high speed single screw ships with relatively fine block coefficient (about .7) were built in which concern with potential vibration problems governed the characteristics of the afterbody. Limited plans were made to evaluate the maneuvering characteristics of the design. The delivered ship proved to be dynamically unstable and would occasionally execute a 360 degree turn without warning [2]. Some Ro-Ro type vessels have exhibited unpredictable behavior during canal transits at slow or medium speeds and have been known to sheer unexpectedly from centerline [4]. A number of classes of bulk carriers with open sterns and low L/B ratios have shown second or third overshoot angles of 50 to 100 degrees during 20-20 Z maneuvers. Note that dynamic instability in some types of ships is not necessarily undesirable, however the degree of instability coupled with other factors such as inadequate rudder size, hydrodynamic plan form area distribution, etc., may produce unpredictable behavior. It is the unpredictable behavior of a ship during critical tight maneuvers which is most disquieting to the shiphandler [2].

In response to situations such as those described above, and similar experiences faced by other maritime nations when an extremely poor maneuvering vessel is identified, the IMO and the USCG have recognized that a potential problem exists and have developed guidelines which may eventually lead to the development of maneuvering standards. Over the past ten years the IMO and USCG in association with Panel H-10 have worked to address the problem of defining maneuvering performance standards. Since 1977, the USCG, in response to IMO resolution A.209 (VII) has required the posting of maneuvering information on the bridge of all commercial ships entering US waters. USCG NVIC 7-89, issued 8 January 1990 directs attention to IMO resolution A.601(15), "Provision and Display of Manoeuvring Information on Board Ships" which supercedes resolution A.209 (VII). It also provides detailed recommendations to implement the regulations contained in the various subchapters of the Code of Federal Regulations (46 CFR 97.19, for example, application to cargo vessels). The "Interim Guidelines for Estimating Manoeuvring Performance in Ship Design" published in January 1985 as MSC/Circ. 389, have initiated the final step by the IMO with development of maneuvering standards for planned introduction in the early 1990's [5].

In the future, the demand to predict the inherent maneuvering characteristics of new designs will increase as will the need for more accurate methods to make those predictions.

#### 4. PANEL H-10 DEVELOPMENT OF THE MANEUVERING DESIGN WORKBOOK

By the end of the 1970's it was apparent that a set of tools suitable for integration into the systematic design process was required to meet the demands of producing controllable ships for the future.

In 1981, at the New York Metropolitan Section of SNAME, Daidola and Daniel surveyed the state of affairs and became concerned with the lack of available design tools. The authors called for the compilation of current maneuvering design techniques in one reference for the use of the designer [6].

Concurrently, SNAME Panel H-10 had been addressing the problem of defining ship controllability characteristics for pilot reference and the future development of maneuvering criteria. Clearly, the problems pilots encountered in handling ships with unpredictable characteristics (commonly called mavericks or outliers) could in part be addressed through proper attention to design. The development of a Maneuvering Design Workbook was established by the late Mr. C. Lincoln Crane, Jr., as a Panel H-10 project following the 1983 SNAME Annual Meeting paper titled "Design and Verification for Adequate Ship Maneuverability". Much of the groundwork for the Maneuvering Design Workbook was accomplished with the 1983 SNAME Paper. The 1983 paper advocated the inclusion of maneuverability as a separate spoke in the "ship design spiral" to ensure that it received adequate consideration during the design process.

The Principles of Naval Architecture (PNA) had been prepared primarily as a technical treatise for engineering reference. It was concluded that the Maneuvering Design Workbook should not supplant PNA, but draw on the reference and augment the material as a practical design guide. To fill the ship designer's need for a practical tool, a different format for the presentation of material was required.

In March of 1986 a "Maneuverability Design Workshop" was held in conjunction with the SNAME Chesapeake Section meeting. The workshop was intended to serve as a forum from which marine industry professionals not normally associated with Panel H-10 could provide input to the project. The basic objectives for the workbook were described to the attendees as well as the perceived requirements for the material, its use and complexity. Working groups were established to deal with several major topic areas encountered in maneuvering design. The groups made recommendations to the panel for ways to address the content and presentation, type of material, and subject areas. As a result of the 1986 Maneuvering Design Workshop, the format, objectives and basic outline of the Maneuvering Design Workbook were established.

By 1988, the Maneuvering Design Workbook was in full scale development. It was determined that each of the sections of the workbook would be written by one or more persons with expertise in that field. The diverse membership of Panel H-10 provided most of the authors. Mr. Tom Robinson was recruited to serve as editor, and as such was responsible for the coordination of the authors and the continuity between sections. A Workbook Committee was established to aid in the review of the material and to coordinate the efforts of Panel H-10.

The Maneuvering Design Workbook is now in the final stages of editing before publication, possibly as a SNAME T&R Bulletin.

## 5. PHILOSOPHY OF THE DESIGN WORKBOOK

In order to provide a practical guide for efficient use in the design process, a unique approach had to be adopted for the Maneuvering Design Workbook. It was decided that the material should be organized in a manner which corresponds to the different levels encountered in the ship design spiral. These levels are conceptual, preliminary and detail. The most logical approach was to arrange the material in the technical sections according to the corresponding application in the design process. Thus, in the conceptual stages of a design, generally accepted rules of thumb, and comparative relationships would be used, as opposed to the preliminary and detail stages where calculations, model tests, and computer simulations, may be necessary. The organization of the material in this manner aids in developing an intuitive understanding for the subject, and tailors the tools to the tasks required at the corresponding stages of design development.

Consequently, the idea of the design module was developed to directly address the maneuvering design spiral (Figure 1). Each module represents a specific subject area in the design of a ship which is impacted by maneuverability considerations. Subjects such as Basic Dimensions and Proportions, Rudder Design, etc., are presented in the design module format. Each module is intended to stand alone and provide sufficient information to start the design process for that subject area.

The modules are prefaced with a table of "Fundamental Rules of Thumb". These are relationships, and notes which can be referenced quickly during the earliest stages of preliminary design. They are taken directly from the texts that follow in each of the sections. The body of the design module provides extensive discussions of the techniques and design goals available to the ship designer. Some of these would be addressed during more detailed levels of design and require study on the part of the reader along with review of suggested reference material such as PNA, Notes on Ship Controllability, etc., before attempting the analysis. Each section should be studied before applying the

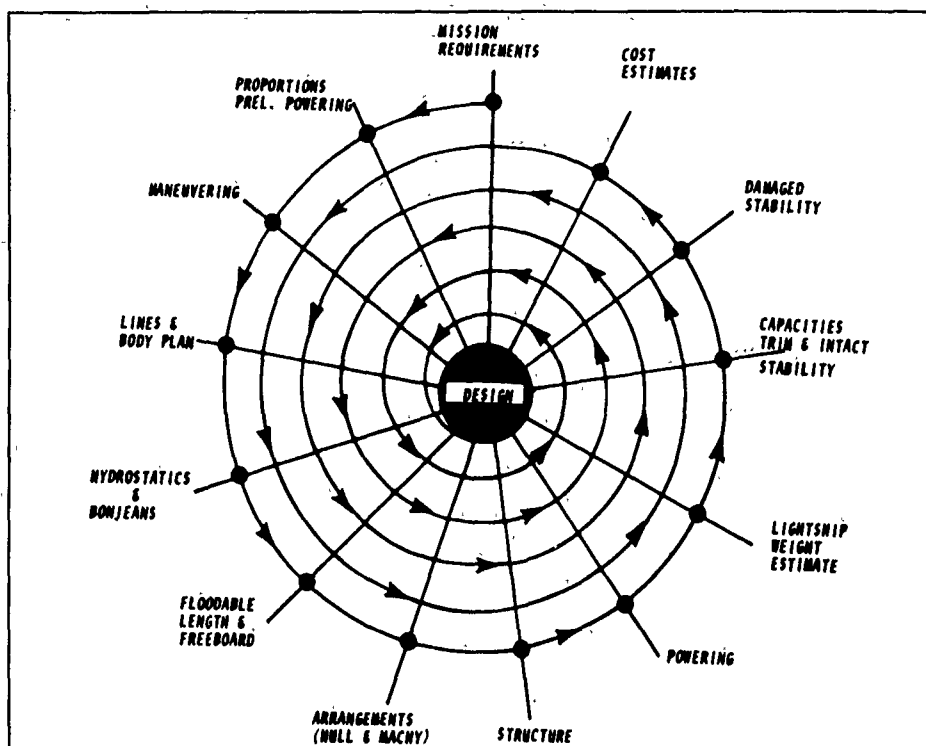


Figure 1 Ship Design Spiral

corresponding fundamental rules of thumb for the first time. This is especially important when the design does not have a parent from which to draw a body of experience. Similarly, caution must be exercised because rules of thumb and guidelines are not always applicable. It may be necessary to undertake extensive analysis to determine the controllability characteristics for a unique ship type. Conversely, only a few fundamental steps may be required to satisfy the designer if he has had experience with the general type of vessel.

One of the basic goals of the Maneuvering Design Workbook is to provide the Designer with sufficient information to determine when the rules of thumb and 'short cut' formulas are inadequate. Unique designs with characteristics which fall outside the normal parameters represent situations which may require the application of much more extensive analyses, such as model testing and computer simulation. It was determined that the scope of technical material should be broad enough to provide the insight required to determine when commonly used short cuts are not enough.

The consideration of maneuverability in the design process encompasses more than the review and application of separate unrelated design topics. There are other factors involved which are woven throughout the overall effort. They fall into three categories, namely Operational, Technical, and Regulatory. A "feel" for these factors and how they affect the design and operation of a ship must be developed in addition to applying rules of thumb and formulas. Each of these facets of a problem should be explored and their respective impacts assessed before an acceptable design compromise is reached. Several introductory sections to the Maneuvering Design Workbook are provided which attempt to illustrate these important areas. They are Operational and Environmental Considerations, Maneuvering Regulatory Standards and Requirements, Assessment of Maneuvering of the Ship in Early Design, and Characteristics of Existing Vessels.

Present maneuverability design practice is still evolving. A document which is flexible enough in its presentation to enable revisions to specific material without revision of the entire document is required. The Design Modules were structured to be independent "modules" each dealing with a specific topic area and can be revised as technology changes without requiring rewriting of the entire document. Present Modules may be expanded and Design Modules can be added to address new requirements in the future. The Maneuvering Design Workbook is presented as follows:

#### Introduction

1. Operational and Environmental Considerations
2. Maneuvering Standards and Requirements
3. Assessment of Maneuvering of the Ship in Early Design
4. Characteristics of Existing Vessels
5. Introduction to the Design Modules

#### Modules

- A. Choosing Basic Hull Proportions and Form
- B. Rudders and Other Control Surfaces
- C. Propulsion Devices and Machinery
- D. Bow Thrusters and Active Maneuvering Devices
- E. Bridge Arrangements for Good Ship Control
- F. Maneuvering Assessment Using Computer Techniques

## 6. DESCRIPTION OF THE DESIGN MODULES

### 6.1 Design Module A. - Choosing Basic Hull Proportions and Form

Operational and economic requirements generally dictate the basic proportions and form of a ship design. Yet maneuvering characteristics may be influenced when selecting a specific set of proportions from a range under study. The selection of length to beam ratio and beam to draft ratio for example, will influence the dynamic stability characteristics of the final design. This module provides an introduction to the relationships between hull form, proportions and inherent maneuverability.

The section is presented as follows:

#### 1 Fundamental Rules of Thumb

The Fundamental Rules of Thumb presented here provide the reader with an overview of relationships discussed in this section. The general effects of changes in proportions, appendages and arrangements are noted for quick use in conceptual design studies (Figure 2).

#### 2 Introduction

The ability to make judgments concerning hull and appendage form, proportions have a profound effect on maneuverability even when constrained by operational and economic criteria.

#### 3 Methods for Assessing Maneuverability

Two of the approaches which may be taken are:

- Steady State Approach

Represented by the diagram of steering

- Dynamic Approach

Time Domain Simulation of transient maneuvers such as that used in trials

What can be done in the absence of specific model test data to evaluate the maneuverability of a design? What may be done to assess maneuverability in the early design stage using these two methods? These questions are posed for the two approaches above.

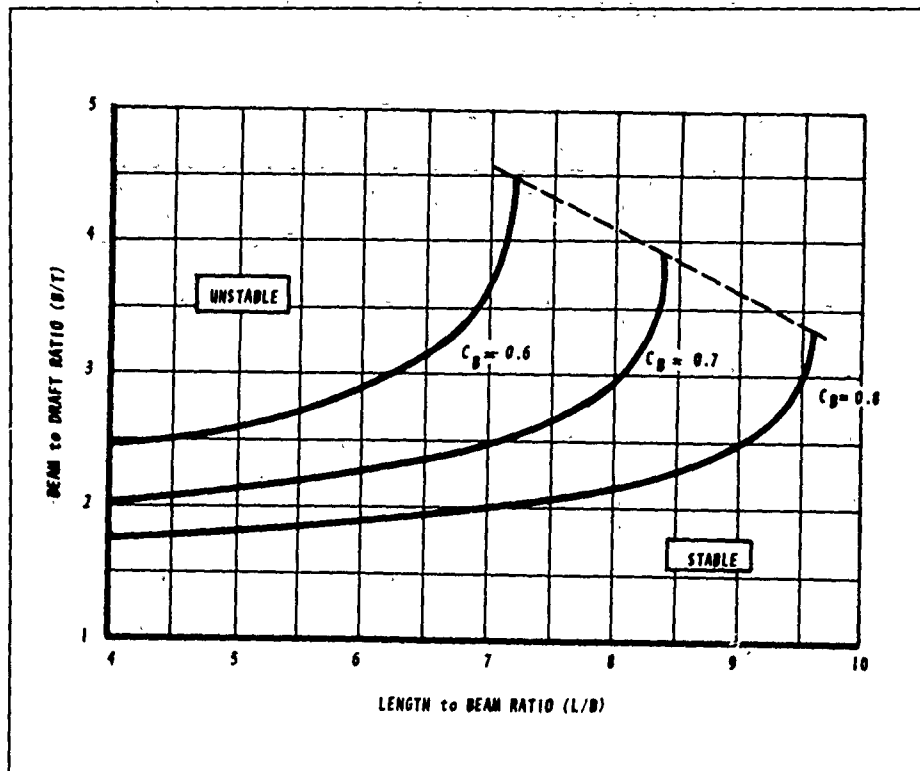


Figure 2 Dynamic Stability Boundaries

#### 4 Relationship Between Maneuverability, Controllability and Hull Geometry

How can specific relationships be understood on the basis of design information that is available? The best guidance is obtained from model test data and simulation studies. However, there are qualitative relationships between design features and measures of maneuvering performance such as the following:

- Stability on Course and Course Keeping
- Turning Ability
- Course Changing and Checking Ability
- Stopping Ability



5 Relationship Between Hydrodynamic Coefficients and Hull Appendage Geometry

A method of estimating hydrodynamic coefficients is required for utilization of either the diagram of steering or time domain simulation. This section presents the current references and techniques which have found application in these two approaches during the early design stages. However, the author cautions that much work remains to be done before an accurate prediction technique is available for use in the design process.

6.2 Design Module B. - Rudders and Other Control Surfaces

The rudder is the primary device used for achieving the desired maneuvering characteristics of the ship.

This section is presented as follows:

1 Fundamental Rules of Thumb

The Fundamental Rules of Thumb provide the reader with an overview of general rudder selection process. The selection of rudder area, rudder type, and rudder clearance constraints are noted for quick reference.

2 Types of Rudder

The three conventional rudder types, the simplex rudder, the horn, and the spade rudder are compared (Figure 3). The selection of rudder area is discussed based on general considerations. The constraints on rudder clearances are described.

3 Basic Hydrodynamics of Rudders

The rudder lift, drag, normal and resultant forces are defined. The location of the rudder relative to the propeller flow is discussed. The considerations for selecting rudder aspect ratio, balance ratio, and section shape are noted. Methods for predicting the rudder hydrodynamic force and torque are mentioned.

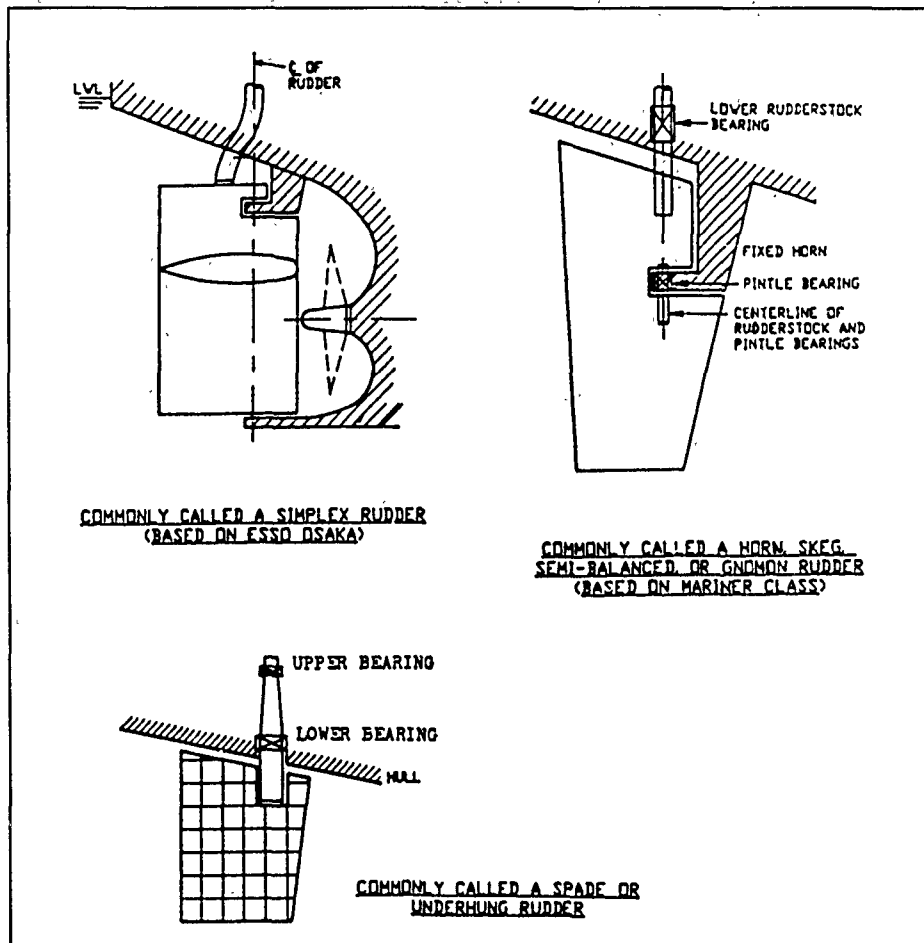


Figure 3 Types of Rudders

#### 4 Rudder Strength

The rudder strength is determined from the predicted rudder forces and moment and the bearing reactions. The bearing reactions are calculated from static equilibrium for the spade rudder. The other rudder types with more than two bearings have statically indeterminate reactions which require more detailed analysis.

## 5 Special Types of Rudders

The special types of rudders mentioned are the flapped rudder, the rotating cylinder rudder and the Schilling rudders. The flapped rudder has a trailing edge flap which moves to an angle relative to the rudder providing additional lift. The rotating cylinder rudder has a spinning vertical cylinder located at the leading edge of the rudder which augments its lift. The Schilling rudders use a special section shape, horizontal end plates at the top and bottom of the rudders, and large rudder angles of about 75 degrees. One or two rudders are used for each propeller, with the twin rudder configuration giving control in all directions.

## 6.3 Design Module C. - Propulsion Devices and Machinery

The characteristics of the propulsion machinery are critical to achieving a vessel possessing good maneuvering capabilities. The attention that a naval architect gives certain design requirements, may be negated if the main propulsor selected cannot provide compatible functions.

For example, stopping and quick reversal may be of critical importance to the ability of a ship to negotiate a particular channel. Yet, if the drive train with the propulsor selected cannot be stopped and reversed in sufficient time, these criteria will not be met.

This section is intended to provide the naval architect who is not versed in marine engineering with a basic understanding of the functional capabilities of typical propulsor and drive train arrangements most commonly used on modern ships.

The section is presented as follows:

### 1 Fundamental Rules of Thumb

This section, provides a table of basic operational parameters for the propulsion plants discussed in the text. These operational parameters consist of typical reversal times, methods for achieving reversal, and operational limitations such as maximum continuous operation astern.

## 2 Screw Propellers.

A basic discussion of the screw propeller is provided describing typical shaft bearing arrangements. Factors that degrade or improve propeller efficiency are presented. Some methods to improve efficiency, such as Kort Nozzles, will have a significant effect on directional stability, and maneuvering while going astern.

## 3 Steam Turbine Powered Vessels

A basic description of the steam turbine and drive train are provided. Typical reversal times, stopping times, maximum horsepower astern (as a percentage of maximum ahead), as well as suitability for slow speed, low power operation for harbor maneuvering are presented.

## 4 Gas Turbine Powered Vessels

The fundamental operation of the marine gas turbine is described. The typical drive train arrangement is presented along with typical operational maneuvering capabilities. Here the author provides the benefits and constraints of the gas turbine when utilized in maneuvering situations. Operational constraints with the gas turbine such as continuous low power operation are highlighted for the awareness of the designer. The relative merits of fixed pitch verses controllable reversible pitch propellers coupled with the gas turbine are reviewed from the maneuvering aspect.

## 5 Slow Speed Diesel Engine Powered Vessels

The characteristics of the slow speed diesel engine are presented. As in previous sections, the author takes great care in detailing typical drive train arrangements. This will set the context for a presentation of the fundamental maneuvering characteristics of the slow speed diesel engine. Included are typical reversal times, minimum required starting air flask capacities, maximum astern horsepower/operating time and minimum continuous ahead rpm.

#### 6.4 Design Module D. - Thrusters and Active Maneuvering Devices

The rudder is the primary device used for achieving the desired maneuvering characteristics of the ship. When the rudder is not effective, particularly at low speeds, thrusters and active maneuvering devices are used to attain the required capability.

This section is presented as follows:

- 1 Fundamental Rules of Thumb

The Fundamental Rules of Thumb provide the reader with an overview of the general thruster selection process. The selection of thruster type, thruster power, and thruster location constraints are noted for quick reference.

- 2 Definition of Ship Maneuvers

The maneuvers of a ship are made up of surge, sway, and yaw motions and combinations of these motions. Using only the rudder(s) and propeller(s) a ship has relatively limited capability to execute these motions at low speeds. Thrusters and active maneuvering devices substantially enhance this capability.

- 3 Types and Sizes of Thrusters

The two basic types of thrusters are propeller and water pump (Figure 4). The relative efficiency, suction location and discharge location of the two types of thrusters are compared. Thrusters which can vary the direction of thrust are described. The size of thruster required may be selected on the basis of empirical relations of thrust or power to the area of the ship above and below the waterline or its displacement, as presented in this module. Its size may be selected on the basis of the thrust required to hold against environmental forces and moments. The size may be selected based on simulations using the dynamic equations of motion. A number of different configurations are illustrated. An empirical relationship of tunnel thruster length to diameter is presented.

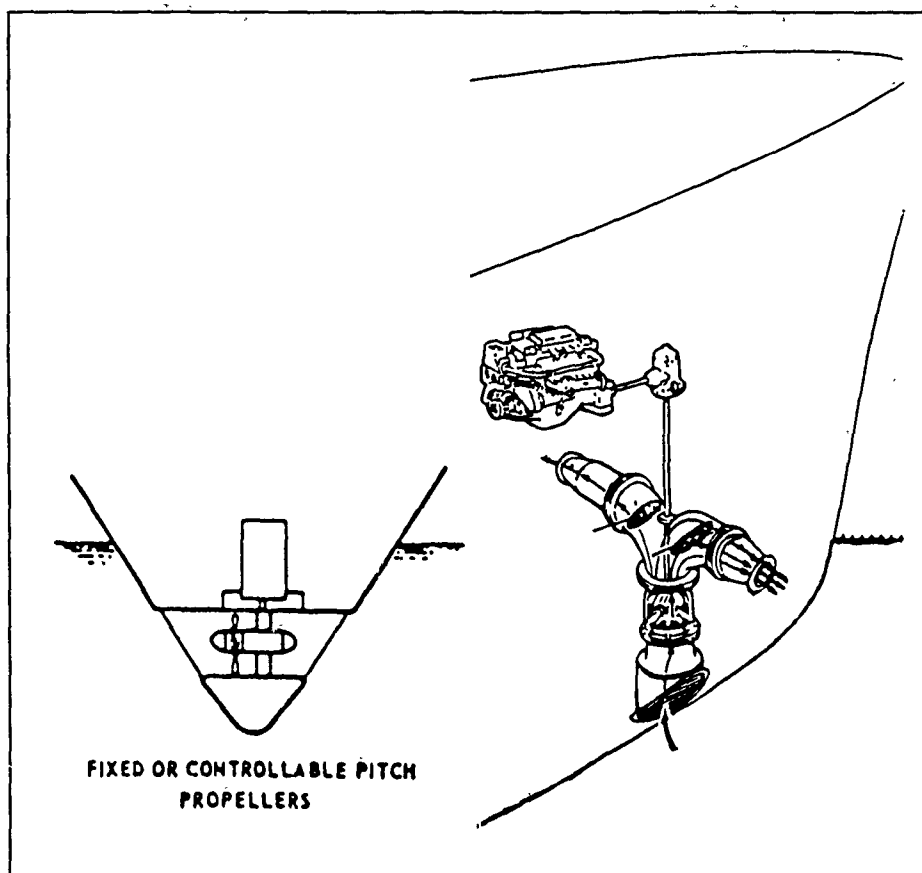


Figure 4 Bow Thruster Types - Propeller and Water Pump

#### 4 Thruster Installation

Considerations of thruster location longitudinally and vertically are presented. The thrusters are most effective when located near the ends of the ship and immersed sufficiently below the water surface.

#### 5 Vertical Axis Propellers

The Vertical Axis propellers have vertical blades which follow a variable cycloidal path to produce thrust, by means of a sculling motion effect, in any direction.

## 6.5 Design Module E. - Bridge Arrangements For Good Ship Control

Perhaps nowhere else in the ship design is the importance of vessel maneuverability as apparent as in the arrangement and design of a ship's bridge. Equipment should be selected and positioned to facilitate the ability of the master or pilot to make judgments and issue commands based on information from visual, verbal and electronic sources. The practice of modern bridge design is changing rapidly with advances in technology, and the increased tendency to reduce manning and watch sizes.

The author, who is an experienced pilot, has written his section with a seaman's eye, but also with a sense of the impact of Ship of the Future technology on his profession where the human factor has not always been considered. His views represent the distillation of years of technical papers and pilots/masters comments. Taking the rapid technological changes into account, he has offered some ideas on what to expect in the future and how to maintain and improve the pilot/ship interface.

### 1 Fundamental Rules of Thumb

Some of the basic ideas and guidelines of this module are presented here. General information concerning the effects of bridge location on perspective, minimum instrumentation, and design concepts are listed.

### 2 Discussion

The concept of the bridge as a Ship's Operation Center (SOC) is developed and defined to have a minimum number of three conning stations. Each conning station is equipped with a suggested minimum instrumentation suite.

### 3 Some Examples of Modern Bridge Design

Several example bridge designs are given. Here the author lists in detail, those aspects of bridge design that are functional from the pilot's standpoint. The concept of the Ship Control Center is presented and discussed. Suggestions concerning bridge designs for reduced manning are provided.

### 4 List of Good Bridge Design Concepts

The details which make for a good bridge design are listed for review. Among these are all around visibility, highly visible primary indicators, low noise levels, etc.

5 Standardization

Some of the aspects of standardized instrumentation as suggested by the author are presented.

6 Bridge Features

The benefits and drawbacks of each of the three major bridge locations are highlighted for review. The locations are forward, midships, and aft. What constitutes an adequate sized pilot house is defined, and aspects of good visibility discussed. Other bridge design features which are critical to the overall function of the bridge are presented with a paragraph discussion for each.

7 Use of Simulation for Bridge Design

The author discusses the degree of simulation that is necessary to fulfill the needs as a design tool and still provide adequate information for the designer when dealing with bridge arrangements and instrumentation.

8 Other Ship Features that Affect Bridge Operations

It is important for the ship designer to be aware of the other areas of the ship arrangement which could obstruct the view from the bridge. These obstructions may be from king posts, containers, etc. Placement of other deck equipment is also of paramount importance.

6.6 Design Module F. - Maneuvering Assessment Using Computer Techniques

The maneuvering characteristics of the ship may be assessed using computer prediction techniques.

1 Introduction

Computer prediction techniques can provide the capability to more accurately assess the maneuvering performance of the ship including effects of the hull, propeller and rudder.



## 2 Ship Maneuvering Equations

The ship maneuvering equations of motion consist of the surge, sway, and yaw equations. Their form equates the inertial and acceleration terms to the forces due to the hull, rudder, propeller, and external forces.

## 3 Mathematical Modeling of Ship Motion in Maneuvers

The mathematical model of the ship hull may contain inertia (added mass), lift (circulation), and viscous (cross-flow drag) components. The model also includes the effects of the rudder and propeller and their interaction.

## 4 Directional Stability and Steering Indices

The linear form of the equations of motions (neglecting non-linear terms) can be solved to determine the stability indices (roots), stability levers, or stability criteria of sway and yaw motion. The linear equations can be used to define the Nomoto-Norrbin steering indices  $K'$  and  $T'$ .

## 5 Estimation of Derivatives

Prediction equations are presented for linear and non-linear coefficients in the equations of motion. The hull, propulsion, rudder, and their interactions are predicted using analytical, empirical, and regression relationships.

## 6 Predictions of Ship Maneuvering Characteristics

The prediction equations allow assessment of directional stability and turning ability of a ship design for variations in ship and rudder geometry (Figure 5).

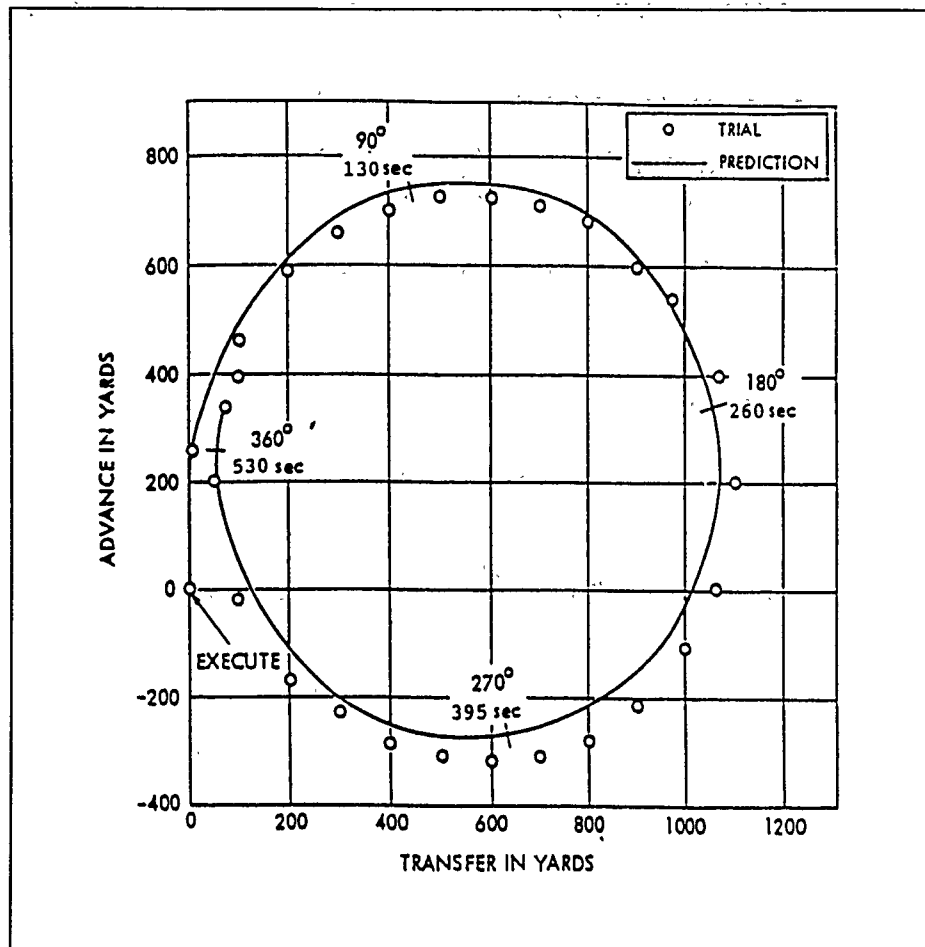


Figure 5 Predicted and Trial Turning Circles for Mariner

#### 7. FUTURE DIRECTIONS

As design requirements have changed significantly in the recent past, so will the future bring further changes. The technology used to meet these requirements is also advancing substantially. The module concept of the design workbook allows for adaptation to these changes.

A. Changes in Design Requirements. New design requirements are being imposed by regulatory bodies on both commercial and naval ships. Additionally new threats to naval ships lead to changes in requirements.

1. Commercial ship designs are now subject to the recommendation contained in the United States Coast Guard NVIC 7-89 [5] to predict the maneuvering characteristics of the ship during design. The recommended characteristics include turning circles, yaw checking, initial turning, course keeping, slow steaming, and stopping abilities. The workbook modules cover the prediction of these characteristics early in the design cycle. It is intended that future workbook modules will be developed to provide for more detailed predictions of these characteristics.

2. Naval ship designs are also under the recommendation to predict maneuvering characteristics during design. Naval ships are further required to maneuver to avoid or minimize threats from weapons. The maneuvers may attempt to reduce the detectability or vulnerability of the ship or increase its defensive capability. At present specific performance requirements have yet to be established.

B. Changes in Technology. A limited amount of research and development in the area of maneuvering prediction technology is underway. As predictive methods are developed which are accurately sensitive to variations in ship hull form, appendages, and propulsion plant, more detailed workbook modules can be developed. The continued development of ship handling simulators for training and harbor design and evaluation should be a subject of the workbook. Simulators have been used successfully to determine maneuvering characteristics during the design of unique ships [7].

## 8. CONCLUSION

The Maneuvering Design Workbook is being developed to help the naval architect adapt to the future trends and requirements mentioned here. The document is intended to address the needs of the naval architect by bringing the available source material together into one document and presenting it in a manner that is straightforward in application to the design process. It is hoped that the work of developing more refined design tools, concepts and techniques will continue in the future, and that the Maneuvering Design Workbook will continue to evolve to reflect those trends.

## 9. ACKNOWLEDGEMENTS

The Maneuvering Design Workbook represents the contributions and authorship of many people spanning the last seven years. The authors would like to acknowledge these people for their efforts.

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## TECHNICAL CONSIDERATIONS IN SHIPS CONTROL SYSTEM PROCUREMENT

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### 1. ABSTRACT

The construction of a warship encompasses a wide variety of components, many of which can be described as traditional while a few represent quite new technologies. An integrated machinery control system comprising distributed intelligent processors is a new technology which is not well understood by shipbuilders and suppliers of naval equipment. Yet it is these agencies which most frequently assume contractual responsibility for the ship construction program.

This paper examines the technical issues surrounding the procurement of a new technology as a minor but vital component of a large ship construction project. The paper focuses on the key technical issues required to provide guidance to the various contractors involved. It specifically addresses the perceived responsibility of the procurement agency. Where appropriate, lessons are drawn from recent Canadian Navy experience.

### 2. INTRODUCTION

The machinery control system for a modern warship has become quite complex. This is due in part to the introduction of high response prime movers such as the gas turbine and in part to the emergence of digital electronics as the technology of choice for ship control.

The application of digital computers to machinery controls is simultaneously piece-meal (as major machinery components introduce unit controllers independently) and integrated (as ship designers wrestle with the system engineering problems of ensuring that the high speed, high energy machinery systems are safely and effectively managed to provide high performance).

Finally, in-service support of shipboard equipment constitutes a very large fraction of a weapons system purchase; perhaps as much as twice the initial purchase cost. This has led to the development of reliability centered maintenance (RCM) which, in turn, requires well organized machinery monitoring functions; these in turn require integration with other systems, many of

which do not reside onboard ship. Thus far, the design of the integrated machinery control system (IMCS) has not been significantly influenced by machinery monitoring requirements.

Canada stepped into the integrated machinery control world in the 1970's with the SHINMACS\* (SHIPboard INTEGRATED MACHINERY Control System) development. Since then, the concept moved forward and an advanced development model was completed. Currently, follow-on versions of the SHINMACS ADM are being installed in the Canadian Patrol Frigate (CPF) and in the DDH-280 Class destroyers as part of the Tribal Update and Modernization Project (TRUMP). Both contracts are well advanced and it is now possible to review these procurements with some hindsight. Since SHINMACS represented such a radical departure from previous control system technology (especially at the time the CPF and TRUMP contracts were signed), these projects presented a number of interesting challenges that are worth sharing with the marine community.

This paper, therefore, reviews the technological impact of modern digital control system technology on a ship procurement program. Emphasis is placed on those aspects of this technology which appears to distinguish it from other more traditional elements of the shipbuilding process.

### 3. PROCUREMENT CONSIDERATIONS

#### 3.1 The Ship Procurement Process Major Stages

In general the process of ship procurement involves a series of discrete steps as follows:

- a. Definition of Requirements
- b. Development of Specifications
- c. Design/Definition Contract
- d. Build/Implementation Contract
- e. Introduction to Service

The definition of requirements must be done by Naval Staffs. They may solicit opinion from a wide variety of experts; however, the recognition of a requirement and the definition of a weapons system which could meet that requirement is a function to be undertaken by members of the profession of arms.

The development of technical specifications for a warship clearly requires input from a wide range of technical specialists. The work of specifying the platform is typically organized by Naval Architects and Marine Engineers knowledgeable in the layout and design of ships. Normally, this group will specify

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\* SHINMACS is a trademark of the Department of National Defence

the overall performance of the ship and constrain the following design effort by mandating certain types of machinery, e.g. COGOG, COGAG, CODOG, etc.

Once the major machinery configuration is defined, a specification is drawn up for all other systems and subsystems, including the machinery control system. It is emphasized that specifications such as discussed herein are generally high level performance oriented documents and are, by definition, imprecise. It is therefore important to realize that a specification is not a design. Thus, the next step is to develop a design which, in today's procurement climate, is often done through simultaneous contracts to industry. This process results in two or more competing designs providing an opportunity for comparison, tradeoff and final selection by the Navy.

The implementation or build step is usually a single contract let to the contractor with the winning design. This contract is obviously large and involves a number of important milestones ending ultimately with test and trials of the completed ship. The implementation contractor is given varying degrees of autonomy by different nations up to and including "total systems responsibility" - the "turn-key" approach.

Finally, as subsequent copies of the ship are being built, the Navy busies itself with the process of introducing the new weapons system into service. This later activity involves establishment of maintenance policies, procedures and facilities, training, and other operational support activities, the specific details of which are dependent on the design of the system.

One very important aspect of the procurement cycle is time. Table 1 provides typical durations for each of the specific stages described above.

Table 1. Typical Duration of Procurement Stages

Procurement Stage	Duration (years)
Definition of Requirements	1 - 2
Development of Specifications	2 - 3
Design/Contract Definition	1 - 2
Design/Develop/Build (1st of Class)	4 - 6
Introduction to Service	1 - 2
	9 - 15

It is noteworthy that the entire process seems to take from 9 to 15 years to complete.



### 3.2 The Contractual Process

Western navies by-and-large procure new ships through a complex contractual process. It is naive to assume that this process goes strictly by the book. Failure to take into account the contractual process can undermine a program no matter how good a design may be from a technical viewpoint:

During the period of specification writing, word gets out to the defence contracting industry that the Navy (name any country) is contemplating building a new warship class. Since the market for warships in most cases is small and such events are relatively infrequent, the contracting community tends to be a lean and hungry group. They struggle competitively for the opportunity to lead in the design/construction of a specific ship. This endeavour involves many pilgrimages to the design authority to make the latter aware of the capabilities of the company. Thus begins a process of advertising, marketing and lobbying which characterizes such projects and defence contracting in the western world in general. Since most of these agencies are system integrators and/or shipyards, they distinguish themselves from one another by developing alliances with key component suppliers. This strategic move is designed to win the prime contract and usually begins in earnest during the process of preparing the specification.

During this phase, it is clearly advantageous (to the prime contractor) to cause specifications to be slanted in a direction which favours their key suppliers. Thus, prime contractors and their key suppliers make every effort to provide information, briefings and related design information to those responsible for preparing the specification. Indeed, it is a well known marketing technique to provide designer input to the specification process in the form of design briefs, studies, etc - free of charge.

It is important to note that nothing about this interaction is wrong or in any way illegal. It is a natural consequence of a competitive market environment. Nevertheless, it can result in some interesting and somewhat anomalous situations.

Clearly, these bargaining and negotiation activities - quite natural attributes of the contracting process - do not stop once the prime contractor has been selected. Various suppliers need to be selected and qualified. Also, many aspects of the design require to be revisited (or indeed detailed for the first time). At this point in the cycle, the first engineering change proposals begin to appear. The Navy's involvement will vary from nation to nation and between contracts but the Navy is invariably the approving authority and must be part of the review process.

The reader is reminded once again of the time scales involved in this procurement process.

### 3.3. Technological Change

Integrated machinery control systems have become a reality because digital electronics has advanced to the point where massive quantities of data can be acquired and processed in real time. In the interests of ship survivability and economy of design, these systems are characterized by distributed processors sharing information on a high speed data bus network. A typical system block diagram is shown in Figure 1.

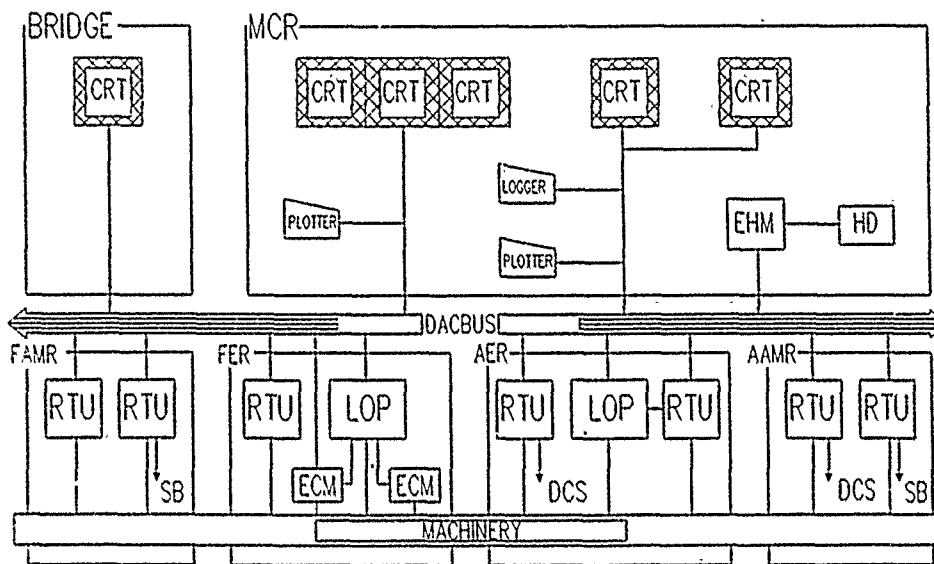


Figure 1. CPF Integrated Machinery Control System

From a military requirements viewpoint, the only practical issues regarding system configuration are related to performance, survivability, reliability, etc. In other words, "user issues". The number of processors, the selection of the bus, the number of buses, etc are (or should be) choices made by designers in order to meet the requirements of performance. Thus, one would expect to see different configurations depending on the technical merits of the components selected for the design.

A problem arises when the rate of change of a technology is incompatible with the time scales normally associated with ship procurement. Table 2 shows the historical development of digital computers over the past 25 years. (1)

Table 2. Development of digital computers

Year	Typical Computer	MIPS	Avg \$/MIP
1965	IBM 360/65	0.6	6,150,000
1970	IBM 370/165	1.9	2,386,000
1975	IBM 370/168	2.5	1,745,000
1980	IBM 3081	10.0	447,000
1985	IBM 3090	50.0	186,000

Source: Authur D. Little, Inc

It is clear from the data presented that this is a very fast moving technology with a typical processor having a "life" of only a few years. Life here is defined as the time required to develop the next generation processor containing sufficient improvements to displace the previous generation in the marketplace.

The significance of rate of change of technology on IMCS (in the larger context of ship procurement) should not be underestimated. Noting that the selected processor largely drives the design of the IMCS, and assuming that the processor's economic "life" is about five years (it could be as low as two), one can expect to see substantial changes in IMCS technology over the 9-15 year procurement cycle. Thus, one can say with certainty that an IMCS will be out of date technologically by the time the 1st of class is commissioned.

Let us consider a real life example drawn from the CPF project. This ship had been specified such that no developmental components or systems were to be included in the design. The first machinery control system identified for CPF appeared to satisfy that requirement; however, for a number of reasons, an ECP was submitted early in the design phase to incorporate a SHINMACS-derivative system. At that time, the AN-UYK series of mini-computers were regarded as the best militarized processors available and had been adopted as the Canadian Navy's "Standard Digital Equipment" (SDE), principally for its combat systems. By and large, all real-time computer processing requirements in CPF were to make use of SDE, although waivers were quite attainable where cause was shown. Since there was general architectural similarity between the IMCS and the Combat System, AN-UYK series computers were being used in the design and build of the SHINMACS Advanced Development Model (ADM) and were included in the ECP.

By the time the revised specifications were written and contracts put in place, it became apparent (through the ADM development project) that the AN-UYK series computers were not up to the task. Their speed placed severe limitations on the performance

of the IMCS. Given that they had been designed primarily for data handling, no analog-digital and digital-analog converters were available. When combined with problems related to time-sharing and interrupt handling, and in order to meet the specifications of performance, a second major ECP was needed.

The subsequent switch to a faster processor and data bus system amounted to a wholesale shift to a new technology. The move required technical evaluation by all parties in the midst of the ship design phase. Furthermore, it called into serious question the long-argued merits of SDE and placed on both the contractor and DND a host of requirements to evaluate and prove a new system while ship design and construction progressed.

Today, with CPF well into trials, several contractors are offering fibre-optic buses which provide another quantum change in performance. Similarly, the so-called high performance processors of the CPF IMCS are now easily surpassed by the high performance end of the personal computers obtainable at any Western consumer electronics outlet.

#### 3.4 Military vs Commercial Components

Military systems development have long been an important technological and economic driver in the Western world. The development of military equipment through the process of contract to industry has provided the latter with an opportunity to learn new things which could then be adapted to commercial markets. Classic examples of this include RADAR, SONAR, jet engines and a significant element of computer technology. If adaptation to commercial markets is successful, the marketplace will dictate further development. This development will usually follow a different path, paced by the volume of sales and general profitability of the commercial product. The governing forces are thus very different from those of a government-funded procurement. In most cases, the pace of commercial development is modest since sales and profitability are insufficient to support rapid change. However, in situations where the sales of a technology expand very rapidly, commercial development will be very fast. As more is learned about the technology, it can be improved at a rapidly lowering cost. As prices come down, sales go up - sometimes quite explosively. This is frequently referred to as "Learning Curve Economics" (2). This was recognized in the automotive industry first by Henry Ford in the 1920's and again in the 1970's by HONDA. The former was dramatic and resulted from the development of the assembly line. The latter was less dramatic but was also driven by learning about the economic advantages of abandoning the traditional vertical integration of the industry (today a car is, in fact, an assembly of parts made by small companies all over the world).

This same situation has occurred in the digital electronics industry driven mainly by the invention of solid state electronics and the consequent opportunity to integrate massive numbers of individual component functions into a single chip. Figure 3 shows the growth of computer memory driven entirely by large scale circuit integration. (3)

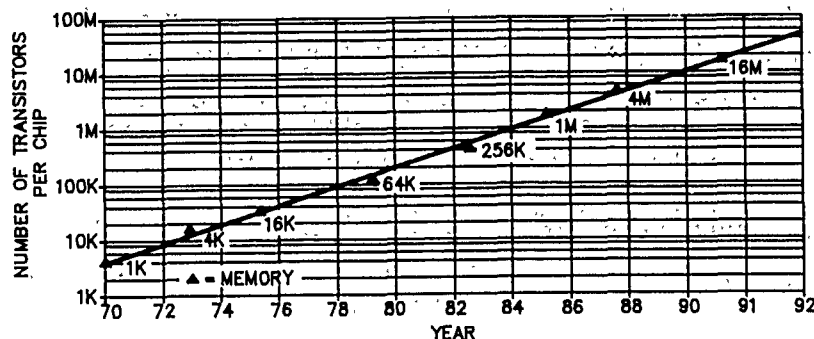


Figure 3. Memory Transistor Integration Trends

As an example, in 1970, the cost of memory was in the vicinity of \$2,000 per 1000 bytes for commercial grade equipment. Today, one can purchase a memory expansion of 2 megabytes for as little as \$1,500. Furthermore, there is no obvious flattening off of the trend. The profitability of successful electronic components is great enough to continue the pace of product development without the need for military funding.

Thus, there is little doubt that commercial development of computers currently far outstrips any military development. There are several important consequences to this situation from the viewpoint of ship procurement.

Firstly, it is foolhardy to assume that a "standard" product or equipment list can be maintained for any length of time. Such a concept implies that sufficient time exists between upgrades to effectively select and enforce the use of such a standard.

Next, the notion of special processors applicable only to a warship is extremely difficult to justify on either performance or cost grounds when general purpose commercial processors are available at a fraction of the cost, suggesting that government ownership of the technology will be most difficult to enforce.

Lastly, the IMCS specification (written typically 3-5 years before design actually begins) must reflect the reality that the IMCS will be developed as part of ship procurement on the basis of "best available" technology. This suggests very strongly that

Navies must recognize the existence of a de facto development phase and should seriously consider conducting this aspect of the ship procurement as part of a recognized development activity..

#### 4. TOWARDS IMPROVED SHIP PROCUREMENTS

If one accepts the reality of rapid technological change within the electronics industry and that a ship procurement program will span more than a decade, then some adjustments to the ship procurement procedures are in order so as to accommodate IMCS. The authors recognize that no two shipbuilding programs are the same; thus, the following sections are presented in no particular order of importance. The purpose here is to share with the readers some of the lessons learned from a de facto system development within a major ship procurement.

##### 4.1 Testability of Specifications

The need for clear specifications is not news. They result in smooth procurements and despite opinions to the contrary, bidders really do prefer them. They avoid confusion and the need to provide large contingencies to deal with vagueness or unknowns.

For those elements of the ship which are truly developed products or, as a minimum, are well known, it is possible to constrain the design simply by reference to such items. For example, a valve might be specified as "XXXXX product or equivalent". Such statements infer that the designer can choose between any number of similar components which have been qualified for Naval service. The further inference is that such a choice is satisfactory and that only system level tests will be required.

An IMCS specification will have to be restricted to general configuration and to performance requirements. The reader is again reminded that at the time the specification is being written, the technology likely to be used in the final implementation is, at best, at a developmental stage. Thus, the specification must be written with considerable attention to testability. In particular, there should be no requirement written into a specification which cannot be demonstrated either by a unit/system test or by inspection of the production process. Since inspection of software production is for all practical purposes impossible, testing is the only realistic option.

##### 4.2 Reliability

Perhaps one of the most abused areas of system design for computer-based control systems is that of reliability. The specification writer needs to be aware that there are two aspects to reliability of a complex system - physical reliability and inherent reliability.

Physical reliability is related to the reliability of basic components which is in turn related to failure modes, mean times between failure, and other data obtained under known conditions.

Inherent reliability is an attribute of the design process over which the developer has some control. Specifically, if the failure rate of a component is known to increase under certain stress conditions, the designer can choose to keep stress low, thereby obtaining better inherent reliability. Similarly, software failures are entirely design-related and thus form part of inherent system reliability.

Physical reliability of a design is based on computational procedures which, in turn, are based on component failure rate statistics, probability theory and the assumption that the control system is inherently reliable. It is common practice to use these techniques to demonstrate the reliability of a design. The specification writer should be aware of this - as should the procurement agency. What will in essence be demonstrated is conformance to an equation. Equating this to true reliability is dangerous and most often wrong. Attempting to extrapolate further without a formal and expensive test program will serve only to promote argument.

Redundancy is commonly used to improve overall reliability of the system. Such an approach can improve the physical reliability by providing backup or alternative path control. This, of course, does nothing for inherent reliability since it is a copy of the same thing. It can, in certain circumstances, make matters worse by increasing the physical complexity, i.e. more failures of a known, physically-unreliable component or subsystem. It must be further noted that switch-over logic (and more components) will be required, thereby introducing its own set of unreliability problems.

The key to good system design is graceful degradation of performance as components within the system fail. Of course, this is the essence of design-related inherent reliability but within the context of a specification of a yet-to-be-developed system, it is next to impossible to prove. Thus the following should be very seriously considered for inclusion in a specification of an IMCS:

- a. Computer modelling of the physical reliability of a system based on components data. This would require the ability to model some of the key design parameters.
- b. Advanced Development Models (ADMs) of the system which enable the demonstration of both physical and inherent reliability of the system.

- c. Accelerated mission testing wherein a system is subjected to tests which attempt to simulate the conditions of age and usage in a shorter time frame.

Of the above, item (b) is considered mandatory. The exclusion of an advanced development model (or service test models, prototypes, pre-production units, etc) for all practical purposes postpones all system testing until the design is complete and a unit destined for a ship has been built. Only at this time can issues of functional testing and reliability be seriously addressed. Furthermore, without an ADM, system changes which appear to be inevitable cannot be examined at all on anything other than the prime equipment.

#### 4.3 Systems Engineering

The rapid growth of technology since the Second World War has allowed the growth and emergence of whole new branches of engineering. Among these new disciplines is the so-called "systems engineer". In the authors' view, no single professional title is more misused and misunderstood today.

If one reviews the course syllabus of virtually any university, systems engineering is synonymous with in-depth knowledge of computers, software and the whole business of linking computers together. Indeed, since so much of the computer industry is devoted to business information systems, the notion of machinery control is a rather insignificant part of such a course of study.

At this juncture, it is possible to state with some assurance that:

- a. university systems engineering courses do not teach much about machinery control;
- b. typical IMCS suppliers are very knowledgeable of electronics, computers, software and such related topics but lack in-depth knowledge of the machinery and systems under control;
- c. traditional marine systems engineers are knowledgeable of mechanical systems but lack detailed knowledge of computer-based control systems;
- d. although overall contractual responsibility for the ship construction phase may or may not rest with the shipyard concerned, the yard expects the IMCS to be delivered as a fully-developed, fully-tested system ready to be integrated into the ship - and to work; and



- e. to the end customer - the Navy - systems engineering means considering all aspects of the "System" including: propulsion machinery; all ancillaries, auxiliaries, their respective unit controllers, monitors; the IMCS hardware, software, sensors, actuators and displays; and the men expected to run the System at the several operating stations provided; yet
- f. the turnkey ship procurement process (with its inevitable multi-layer contracts) does not cater for system engineering as currently perceived or defined in e. above.

In view of the fact that a ship is procured in the manner described herein, there is a real need for a Navy-driven systems engineering group to provide a watch dog role on the entire issue of systems engineering. Such a group requires knowledge of all aspects of the system but should not be aligned with any specific element of the procurement chain. In short, they must be a manifestation of the adage:

"Good systems engineers never fall in love."

#### 4.4 Test & Trials

Regardless of the nature of the contract (fixed price with milestones or turnkey), the practice of contracting with the prime contractor and his various suppliers to design the test and trials program is invariably troublesome.

It should be fundamental to any procurement that the buyer establish the acceptance criteria independent of the suppliers. This implies having sufficient knowledge of the system to enable him to design his own tests. Furthermore the planning and organization of the test program requires the buyer to investigate the design. The insight obtained from this process establishes a much better understanding of the design and potential problems to be encountered in service. For an IMCS, testing must be conducted at several distinct levels:

- a. Developmental or component level;
- b. System level at the factory; and
- c. System level in the ship.

Once more, the developmental nature of an IMCS emerges. The reader is again reminded that an IMCS is highly tailored. The selection of distributed processors, their degree of remoteness, their functionality are all dependent on the design of the ship and her machinery. Thus, critical timing issues can only be resolved at design time. Communication software will require to be tailored to the situation and all "tactical" (control and monitoring) software will be ship-specific.

Testing of an IMCS must therefore begin with individual components and be organized to progressively build up confidence in the system as more components and functions are added. This process identifies weaknesses in the design and forces iterations to be undertaken. Seldom are component tests completed or repeated at a level satisfactory to an unbiased external scrutineer. This suggests once again the need for the buyer to specify, and to participate in, the tests. One final comment on component testing is noteworthy. They are seldom, if ever documented and made available to the Navy, yet would be a remarkably valuable record of what was actually tested at the component level once higher level testing is undertaken or after the system has been commissioned. The need for thorough component tests with complete documentation and reporting cannot be overstated. Only rarely is it considered part of the normal contracting process.

Factory acceptance testing at a system level is the normal entry point for Navy observers insofar as test and trials are concerned. Such tests are currently designed by the control system suppliers and approved by the Navy. The complexity of an IMCS is such that without the aid of capable tools to review and validate the test plan and procedures, approval may well be given with a less-than-complete inspection of the test program. Such a practice is unsatisfactory; the preferred approach is the preparation (again, by the Navy) of an independent test plan and associated procedures. Practically and within the current procurement climate, this is not possible. As a minimum therefore, the test plan and procedures should be themselves tested against a capable simulation of the system. This removes most of the subjectivity from the process and allows the establishment of acceptance criteria independent of the supplier.

#### 4.5 Personnel Implications

One last procurement consideration should be addressed; that is, the impact of this rapidly changing technology base on personnel and training structures. Although not necessarily defined as technical procurement considerations, it is often the technical authority's responsibility to ensure that changes to occupational structures and training (which result from changes in the technology base) are initiated. Such changes generally take at least as long as the system design process itself; moreover, personnel systems are generally resistant to change where the need for change is not readily assessable and quantifiable. Recognition of the need for on-going development and a separate development activity within major procurements could provide the tools needed to support such an assessment early enough in the ship design process to provide trained tradesmen when they are needed.

## 5. CONCLUSIONS

This paper has examined the relationship between the major stages of a warship procurement process and the introduction of an Integrated Machinery Control System into that design, noting that the contractual process can often have an unexpected impact on the actual specification of the ship and its control system. Given the inevitable conflict between a long warship procurement cycle and the pressures imposed by high rates of technological change, commercial development factors, and the "difficulties" associated with hardware standardization, it has been concluded that the specification of an Integrated Machinery Control System must reflect the reality that the system will be developed as part of the actual ship procurement process. As a consequence, it has been argued that the existence of such a development phase must be formally recognized and either incorporated as part of the warship procurement process or catered for through a continuous (iterative) development and specification activity.

Recognizing that the warship design and build activity will incorporate an IMCS development component, it has been argued that much greater attention must be paid to all aspects of the testing process: production of truly testable specifications; provision for more extensive modelling and testing of the complete control/plant system; and the need for independence from the Prime Contractor during the key phases of test plan development.

It is concluded that if a continuously-advancing development strategy is pursued, these requirements can be satisfied despite the "external" economic and technological pressures. In this manner, reliable and technologically-modern integrated control systems can be introduced into warship procurement processes with much greater confidence.

## 6. DISCLAIMER

The opinions expressed herein are solely those of the authors and are not necessarily endorsed by the Department of National Defence, Canada.

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## **AUTOMATION OF WARSHIP POWER SYSTEMS**

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### **1. ABSTRACT**

This paper presents the design of a warship power system and its associated control for a frigate sized vessel. The key features of the design are increased survivability together with a high degree of automation.

The design process in general is acknowledged to be an iterative loop, however, the judgement made in this case is that designing to meet the survivability criteria first will be the most productive starting position. A simple method of quantifying vulnerability is proposed and used to compare competing power distribution arrangements. As a result a four switchboard ring main configuration is proposed adaptable to both conventional mechanical and electrical propulsion.

The control system architecture is then examined, it is concluded that the control should be distributed and embedded within the power generation and distribution equipment. This leads to an inherently "Fail Set" design. Finally, an integral feature of distributed control is the need for secure communications between plant controllers and Man Machine Interfaces (MMIs). Consideration of available technologies results in the proposal to adopt a token passing ring dual redundant data bus.

### **2. INTRODUCTION**

The requirement for electrical power on a modern frigate is critical for the successful fulfillment of the vessel's many and varied roles. This requirement is reflected in terms of the power system performance to meet the quality requirements of the user; the need to provide a reliable and secure supply; and the ability to survive damage and continue to supply essential services. These can be summarised as below:

- Sufficient Performance in terms of:
  - Quality of Power Supply
  - Weight and Volume
  - Cost of both Equipment and of Through Life Cost
- High Availability of supply to the user
- High Survivability against action damage

It is the later requirement which distinguishes the warship power system from the commercial equivalent.

In discussion with the Procurement Executive of the UK Ministry of Defence the need was identified for a warship power system that provided both improved survivability and economy of operation in terms of manpower and fuel costs. Automation has been employed extensively in merchant naval vessels to reduce operating costs and a similar philosophy can be applied to naval vessels.

However, automation also has a major impact on survivability. A vital feature of the power system is its operational ability to withstand action damage. Key personnel may be injured and equipment destroyed. Under such scenarios the power system should be capable of autonomous operation. To achieve this it must clearly offer graceful degradation allowing attention to be given to critical survival tasks elsewhere and for itself to be reconfigured when opportunity arises.

The need for improved survivability is clearly desirable, although this does imply a cost penalty; however, recent experience has demonstrated that existing systems are vulnerable to Complete Loss of Electrical Power (CLOE) when subject to action damage, hence risking loss of the vessel. It is suggested that the criteria to be met is that the power system should continue to function, albeit at a lower capacity, after sustaining major damage, such as a direct hit by surface to surface missile. Clearly meeting this requirement will have a very significant effect upon the overall system design. As a result it is this survivability criteria that will be considered first in the iterative design process. However, before tackling this question, there are a number of management and procurement issues to be resolved.

### **3. MANAGEMENT AND PROCUREMENT**

The electrical power system is in the larger context a subsystem of the overall platform; this includes propulsion, auxiliaries, steering/stabilization and most importantly damage control. Its position in the platform is shown diagrammatically in Figure 1. The present tendency is to move towards higher levels of integration, hence the concept of an integrated platform management system (IPMS) is highly topical. Therefore, it is likely that future electrical power systems will be designed within the framework of an integrated platform. The nature of this integration needs to be considered before proceeding with the design issues related to the electrical power system.

The concept of IPMS, as currently discussed, varies from the idea of a complete amorphous system which performs all the platform functions, to that of a procurement and management activity in which operational and implementation issues are resolved at a high level. In this paper the latter view is favoured. Hence IPMS is seen here as an activity undertaken at the earliest stage in the design cycle involving a mixture of skills, namely: management, procurement, operational and engineering. At the highest level the platform is seen to comprise the following major systems:

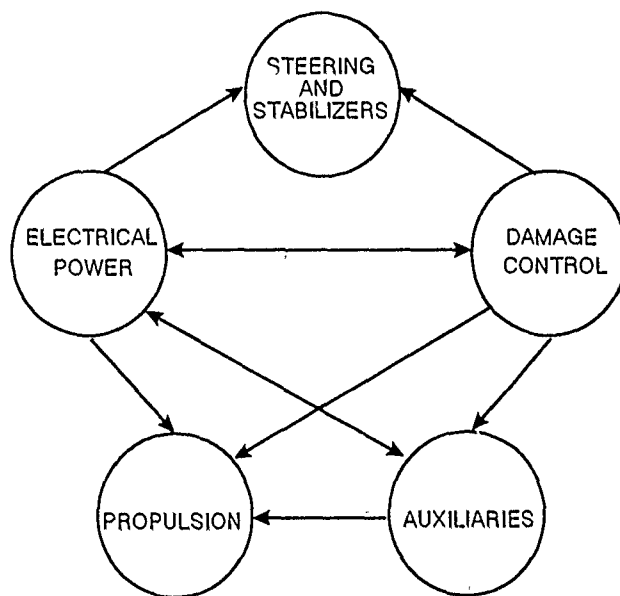


Figure 1. Platform System Interfaces

- Propulsion
- Auxiliaries
- Steering/Stabilization
- Damage Control
- Electrical Power

The IPMS would examine the interaction between these systems by analysing the subsystem interfaces. Hence a significant part of IPMS would revolve around communications. In implementation terms this would take the form of a data bus to which local controllers would connect. Hence it would seem perfectly reasonable to design the electrical power system as a self-contained package, either sharing a common IPMS data bus or connected to other systems via data bus gateways.

The above point of view is further supported by the fact that the electrical power system has quite different design and operational requirements to other platform systems. Hence for the purpose of this paper it is assumed that the electrical power system can be designed and procured as an identifiable subsystem communicating to other subsystems via data bus gateways. This results in a system which is manageable from a procurement point of view reducing the problems normally associated with large scale systems. This includes Programme Management, Testing and Acceptance,

Commissioning and Through Life Maintenance. This view is reflected in Figure 2 in which the IPMS comprises three major subsystems.

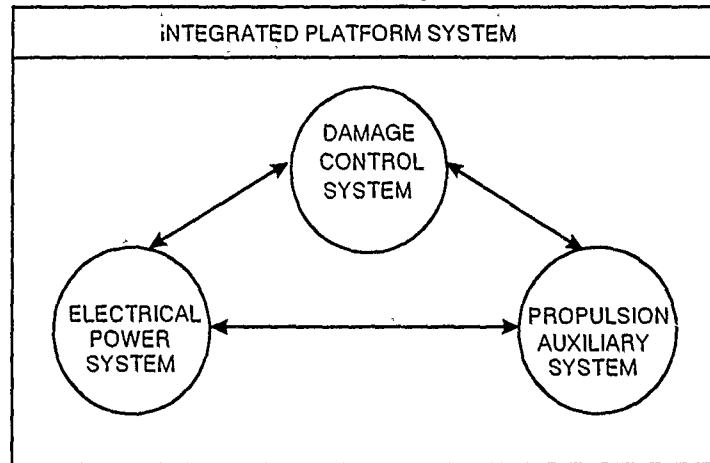


Figure 2 - An Integrated Platform

Finally, it is highly likely that future frigates will be equipped with electrical propulsion. The question then arises should the electrical propulsion system be integrated with the service electrical power system. In brief, the requirements of each are given below:

- (a) Propulsion, requires large dynamic range of power with good overall availability, however it can tolerate short periods of outage during re-alignment operations.
- (b) Service Power, requires a relatively small amount of steady power of good quality with continuous availability.

It is clear that from a design point of view these are widely different requirements, suggesting different design aims and methods. It is for this reason, that the electrical propulsion power system is considered, from a control aspect, to be an integral part of the propulsion system. Therefore, this paper examines the design of the service electrical power system integrated at a higher level into an IPMS.

#### 4. SURVIVABILITY AND VULNERABILITY

##### 4.1 Definitions

Vulnerability is the term used to encompass the likelihood of damage to the power system due to one or other of the following:

- Fire
- Flood
- Human Error
- Sabotage
- Action Damage

For the purpose of this discussion only the effect of Action Damage is investigated. Damage from Fire and Flood is considered to be a secondary effect of action damage, which will involve a given compartment or watertight zone.

Damage due to Human Error is a function of the MMI and the system design in terms of automation and error checking. Likewise sabotage is considered to be either a subset of Action Damage or related to MMI operation.

Hence for the purpose of this discussion, vulnerability is defined as the probability of loss of a specific level of service subject to the vessel sustaining a given action damage.

Now to calculate the vulnerability of the power system the following information is required:

- Nature of the Weapon
- Strength and Ruggedness of the Vessel
- Ruggedness of the System Equipments
- Layout of the Equipment in the Vessel
- System Architecture and Redundancy

Clearly at an early design stage not all of this data is available. Hence for the first design iteration only the system architecture is examined against a given criteria of damage radius. This together with the following assumptions is used to estimate the system vulnerability.

- (a) The sustained damage is contained by a damage circle of specified radius.
- (b) The system is considered to be a collection of equipments having a vulnerable area normal to the attacking weapon.
- (c) The likelihood of damage is taken to be equal over the entire effective area of the vessel.



- (d) Generator services such as Fuel, Air, Lub oil, etc are not included in the analysis at this stage.

On this basis vulnerability is given by:

$$\text{Vulnerability} = \frac{\text{System Effective Vulnerable Area}}{\text{Total Vessel Vulnerable Area}}$$

In which Effective Vulnerable Area (EVA) is a measure of the equipment size inclusive of damage radius. It is calculated using the following heuristically derived equation:

$$\text{EVA} = [2R + (L.H.D)^{1/3}]^2 \quad (\text{m}^2)$$

In which R = Damage Radius  
L = Length of Equipment  
H = Height of Equipment  
D = Depth of Equipment

In the case of feeder cables the following expression is used:

$$\text{EVA} = R.L \quad (\text{m}^2)$$

In which L is the cable length of which it is assumed that only 50% is vulnerable. These equations are represented from reference (4) a recent study report.

#### 4.2 The Supply Chain

To illustrate the power system vulnerability, Figure 3 is presented, this shows the equipments required to provide electrical power at the user terminals. If, for the purpose of discussion, it is assumed that vulnerability is a function of the supply chain length, then it is clear that vulnerability is minimised by the following precautions:

- (a) Minimise the total length from fuel source to user.
- (b) Provide alternative supplies in the chain as close to the user as is practical.
- (c) Maintain good separation between normal and alternative paths.

This is standard practice in the design of any warship system, Section 4.4 and 4.5 attempts to quantify the gain in applying this type of precaution to the power system, using the definitions given above.

#### 4.3 Power Distribution

The supply chain vulnerability has been examined for a number of configurations. Three of these configurations are described below and are the subject of the vulnerability calculations presented in the subsequent sub sections:

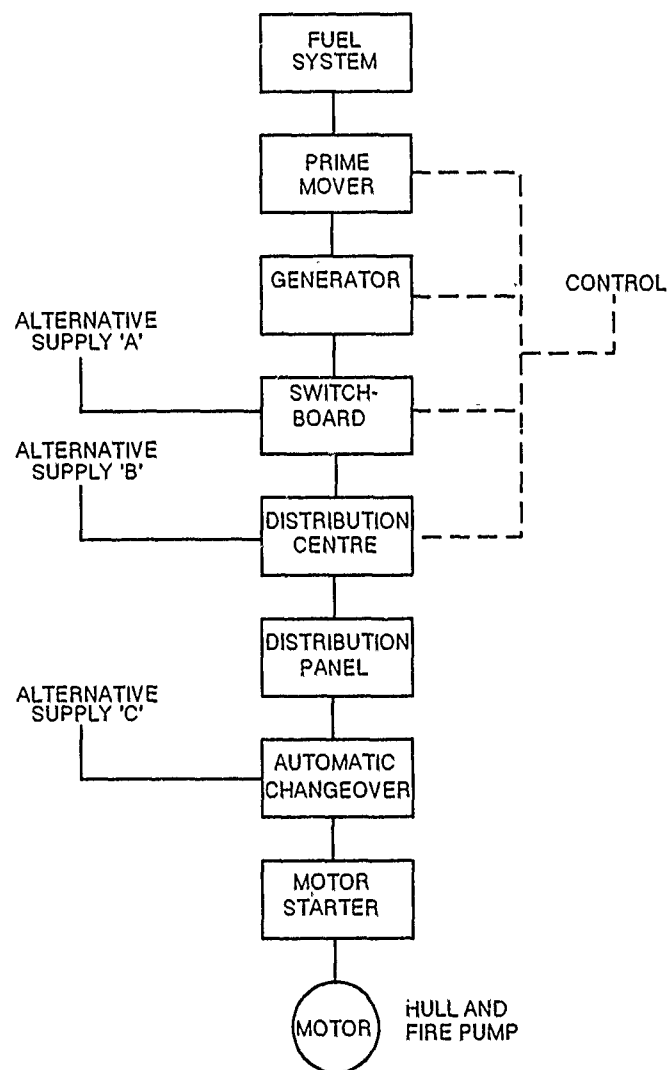
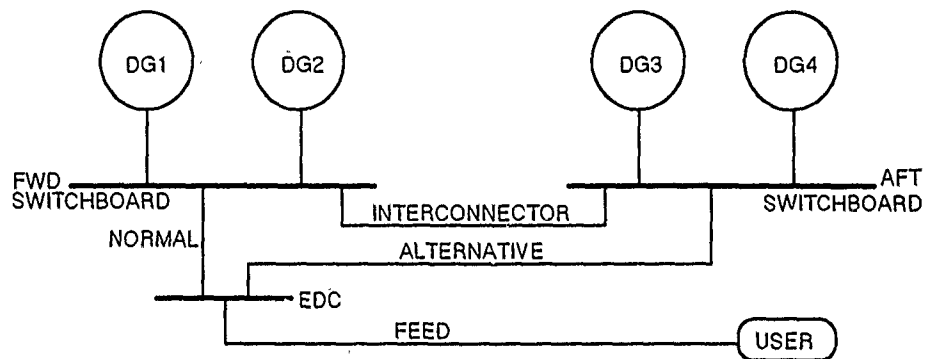
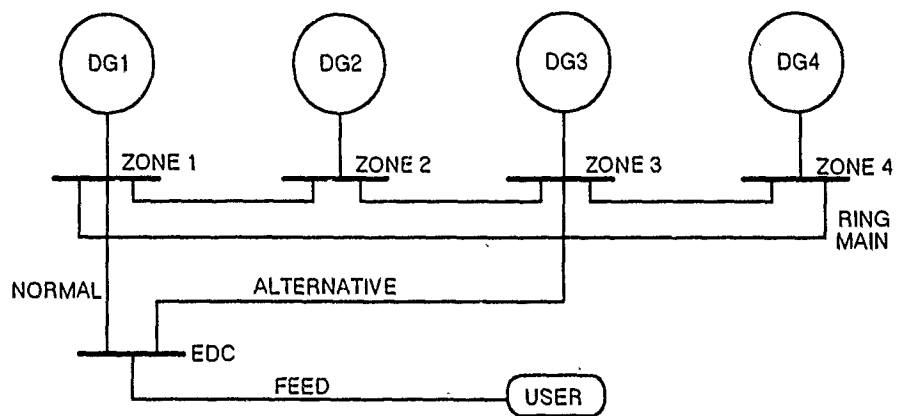


Figure 3. The Supply Chain



NOTE: 1. 2IA system has generators in same compartment  
 2. 2IB system has all the generators separated in different compartments

a) System (2IA) and (2IB)



b) System (4R)

Figure 4. Power Distribution Networks

(a) Two switchboards with Interconnector (2IA)

This is a basic arrangement for almost all existing frigates. The system is usually operated split (interconnector open), with normal and alternative feeds being derived from each switchboard respectively. In this configuration it is assumed that generator pairs are co-located in the same compartment. Hence each pair of generators becomes effectively a single unit from a vulnerability point of view.

(b) Two switchboards with Interconnector (2IB)

This option is identical to (2IA) above, with one exception, namely; each of the four generators is located in a physically separate compartment.

(c) Four switchboards with Ring Main (4R)

This represents a new arrangement for warship power systems distribution. At this stage no assumption is made about how the ring will be operated. (Split, parallel open or parallel closed).

These options are shown in Figure 4.

#### 4.4 Vulnerability of Supply to User

Using typical values for equipment sizes and cable lengths, calculations have been undertaken, reference (4) to derive the relative vulnerability for the options described above.

In each case the length of the cable between Electrical Distribution Centre (EDC) and the User is kept as a variable. The relative vulnerability is for the loss of supply to a given user as a function of the power distribution arrangements and the cable length assuming a direct hit by a weapon having a damage radius of 2 metres. The particular scenario chosen is based upon having one DG set initially out of commission. Also of the remaining three DG sets it is assumed at least two sets are required to service the ship load.

The results are shown in figure 5.

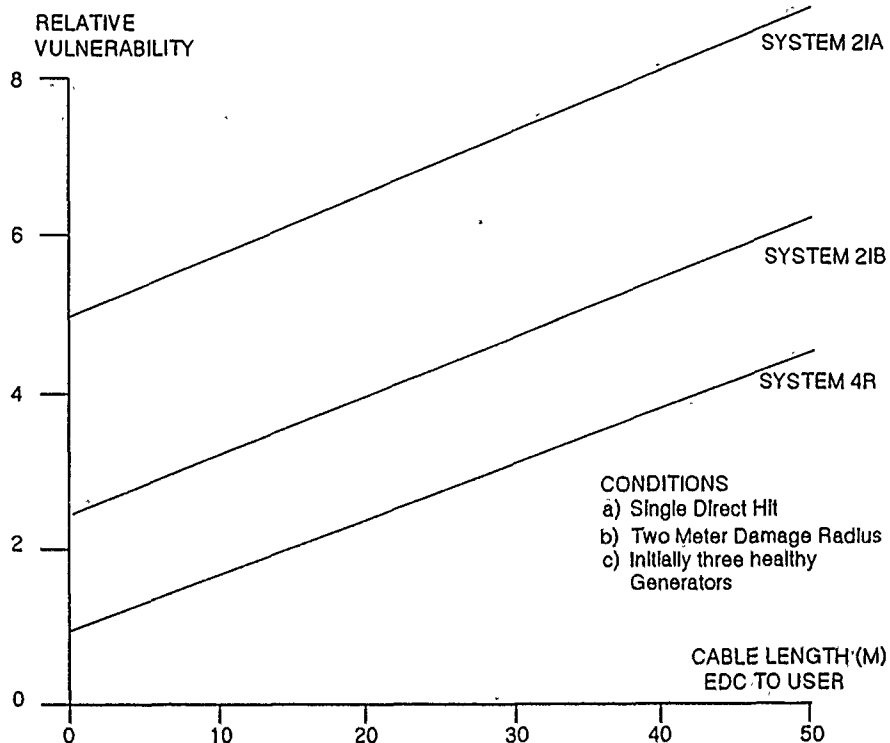


Figure 5. User Supply Vulnerability

#### 4.5 Vulnerability of Complete Loss of Electrical Power

The assessment of relative performance for the three options under consideration in respect of vulnerability to CLOE, has been calculated in reference (4), by assuming a number of incidents. Each incident has associated with it the probability of CLOE. In practice a CLOE would only normally occur following a succession of somewhat unrelated incidents. Hence the calculations presented here are based upon a sequence of five random incidents. This shows the increasing likelihood of a CLOE with each progressive incident. A CLOE is defined to be a complete loss of electrical power, such that power is lost at all main switchboards.

The results are shown in figure 6 for the three distribution configurations.

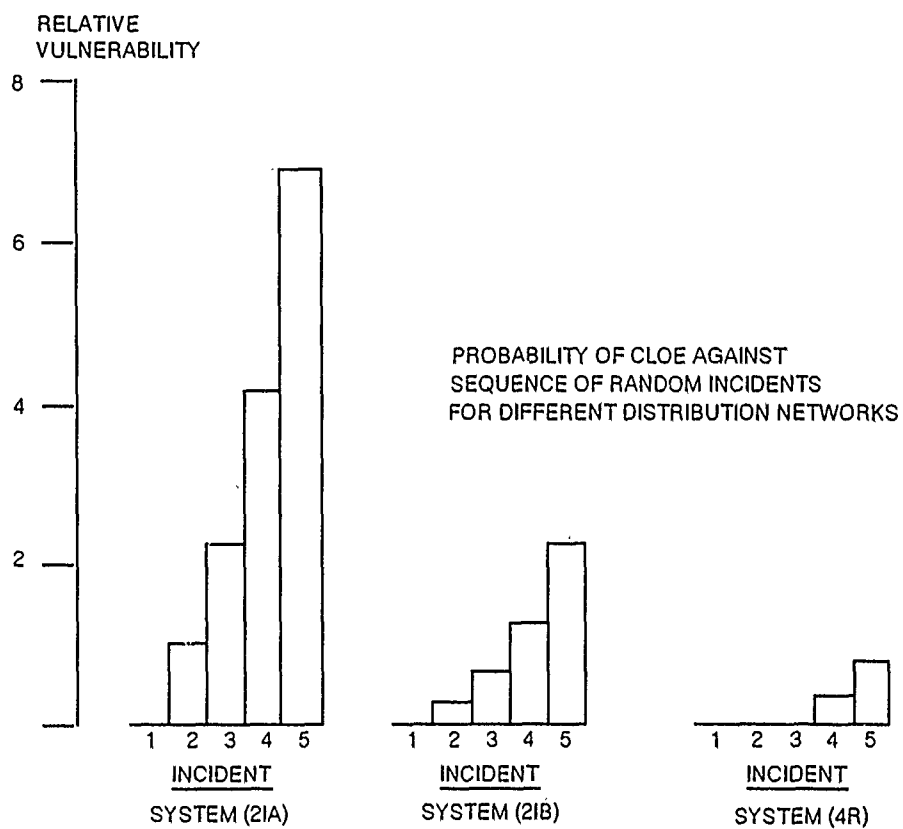


Figure 6. Vulnerability Cloe

##### 5. PROPOSED POWER DISTRIBUTION ARRANGEMENT

Based for the most part on the work done in connection with vulnerability a four switchboard power system is proposed and is shown in figure 7.

The key features of the configuration are:

- (a) Four switchboards connected by a ring main.
- (b) One switchboard located in each of the four major warship zones.
- (c) Generators located in separate compartments to minimise vulnerability.

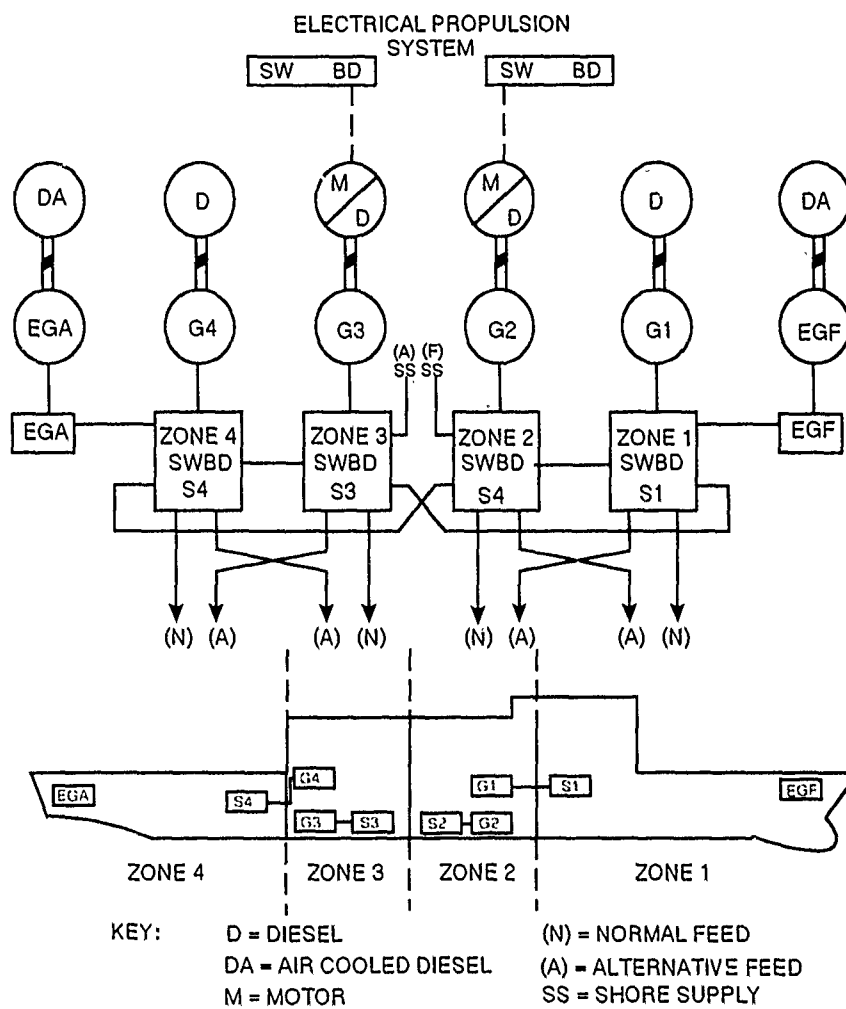


Figure 7. Proposed Distribution Scheme

- (d). Generators located in mid ships zones 2 and 3 only; to minimize exhaust, noise, service and access arrangements.
- (e) Allowance for electrical propulsion via the options of driving generators 2 and 3 from motors connected to the propulsion power system.

At this stage the option is maintained to operate the power system in one of a number of alignments, namely:

- (a) Split any possible combination.
- (b) Parallel with the ring main Open.
- (c) Parallel with the ring main Closed.

It is intended that the operator retains this operational flexibility to choose the best alignment to meet the current circumstances.

ARM studies have been conducted on this four switchboard arrangement and on a two switchboard configurations for comparison. Representative data has been used. The conclusion drawn is that although the four switchboard configuration uses more components the effect on ARM performance is negligible in comparison with existing systems. This arises because the prime mover ARM figures dominate the overall system performance.

In the case of electrical propulsion where motor generator sets are proposed a number of questions are outstanding, namely; (a) the method of power sharing, and (b) the need for reversing power at the MG set. These questions are topics of further work.

## **6. CONTROL SYSTEM ARCHITECTURE**

### **6.1 Background**

Present day systems associated with the two switchboard configuration have a hierarchical control structure based upon:

**Primary** - Overall Power System Control, located at a single position within the Ship Control Centre.

**Secondary** - Control of one switchboard and associated generators, located adjacent to the switchboard.

**Tertiary** - Control of each generator locally at switchboard or Local Control Panel.

Figure 8 shows this hierarchical structure.



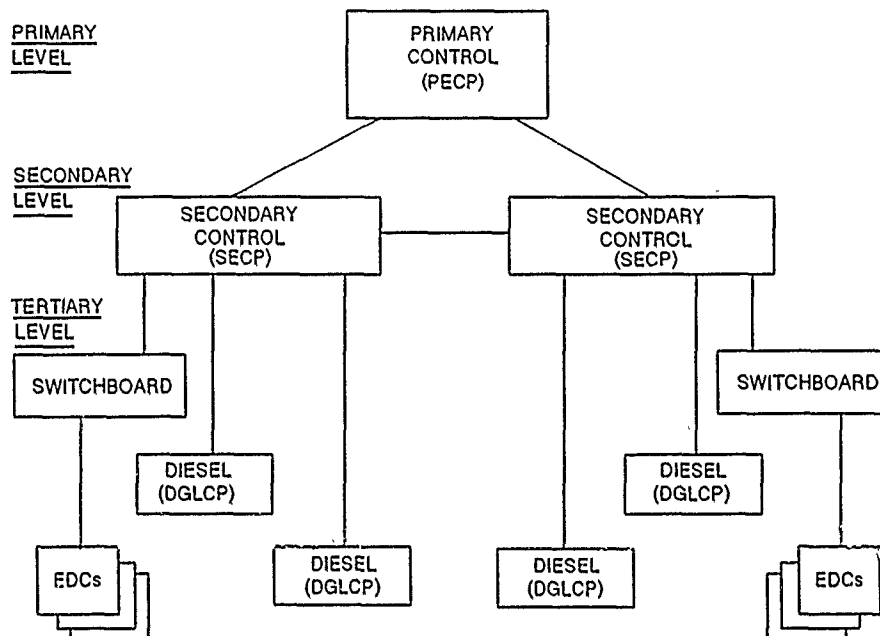


Figure 8. Present Day Control Architecture

## 6.2 The Case for Distributed Control

In Section 4 the case was made for a four switchboard ring main connected power system. In selecting this configuration reduced vulnerability was the prime aim. It is clear, that in order to maintain the degree of isolation between elements of the power system, the control system positions themselves should be local with the switchboards. This precludes the conventional single primary and two secondaries configuration.

Hence it is proposed that each of the four switchboards has integrated within its frame, a control position and associated electronics together with the protection equipment. Each control position will control the operation of its associated switchboard and generator, the generator being controlled via a Diesel Generator Local Control Panel (DGLCP), Governor and Automatic Voltage Regulator (AVR). Furthermore, in order to maintain low vulnerability and consequently high survivability, each controller at this level will be capable of maintaining automatically, the safe and secure operation of its section of the power system; regardless of the ability to communicate with other sections of the power system.

The question that remains relates to the nature and form of primary control. Present systems have a single primary control position. This is

vulnerable and inflexible. The preferred solution would be for multiple primary control positions. If this were the case primary control could be taken at one of many positions to suit the operational circumstances. Hence in a damage situation control could be passed to the Damage Control Centre or it could be taken at a switchboard MMI during commissioning and maintenance operations.

### 6.3 Multiple Primaries

The major difficulty to overcome with multiple primaries is related to control transfers, loss of primary control and the associated control arbitration. These problems can be significantly reduced if all data is held locally only and control is configured to operate on the current data set passing change data only. This means that the primary does not require memory other than a short term buffer. Hence in the case of a control transfer the two primaries would not need to exchange data bases for initialisation and the transfer would be bump free as only control changes are output. This arrangement also implies a flexible data bus communications network.

To summarise the key features needed for efficient multiple primaries are as listed below:

- Data held locally only at DGLCP's, switchboard secondaries, etc.
- Compact Control Algorithms requiring short term buffer memory only.
- Primary Control of electrical plant to be provided by change data only.
- Data Bus communications between all control equipments.

In this scheme each secondary would broadcast its current status periodically; the current primary control position would interrogate the complete data set and compute the change control data for transmission to each secondary. If control was lost the secondary would continue to exercise control over its section of the power system to ensure safe operation.

Initial investigations suggests that such a scheme is feasible. However, it is clearly an area that requires future work leading eventually to either prototype trials or computer simulation evaluation.

### 6.4 Distribution of Control Intelligence

The performance of an automated power system in terms of ability to maintain power supplies to consumers under increasing levels of equipment failure and action damage, will depend on how the automation intelligence is distributed through the system. An automatic system needs to be able to progress through a process of graceful degradation in the same way as a manually controlled system. Certain functions, those associated with normal peace time operation are managed from a central computer, whereas critical functions associated with a particular generator need to be capable of automatic control at a local level.

This requirement leads to the concept of a multi layer control system

**LEVEL 1** Control of the complete power system from a central position (or positions).

**LEVEL 2** Local control of each generating station

**LEVEL 3** Local control of sub system devices (eg Automatic Changeover Switches (ACOS), AVR, etc.)

The control computer required for level 1 control can be located at one position in the ship, or it can be duplicated. The active control centre can be selected manually or automatically by a preset order of preference.

In the event of failure of the level 1 control system at a particular generating station, then that station will continue to run in level 2 control only.

Level 3 control devices are those which operate completely independently eg Automatic Changeover Switches.

#### **6.5 Distribution of Control and Monitoring Functions**

Control and Monitoring functions are distributed between levels as follows:

##### **LEVEL 1**

System Configuration	Operational State Control dependent on- System Health Operation Economy Balancing of running hours Propulsion requirements
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System Health Monitoring  
System Configuration Monitoring  
System Power Monitoring

##### **LEVEL 2**

Generator Control  
Generator Monitoring  
Switchboard Control  
Switchboard Monitoring  
ROCOS Control and Monitoring  
Load Shedding Control and Monitoring

##### **LEVEL 3**

Diesel Governor  
Automatic Changeover Switches  
Automatic Voltage Regulator

## 6.6 Data Communications

Examples of the information which needs to be exchanged are as follows:

### PRIMARY

- Generator power loading
- Interconnector Import Export Power
- Generator Health
- Changeover Switch Control
- Changeover Switch status
- Hours Run
- Circuit Breaker status
- Level 1/Level 2 Computer health
- Operational state

### SECONDARY

- Circuit Breaker Control
- Circuit Breaker status
- Changeover Switch status
- Alarms and warnings
- Current
- Voltage
- Power
- Power Factor

Note that where Remotely Operated Changeover Switches (ROCOS) are used they need to be controlled from Level 1 under normal circumstances, but should be capable of Level 2 or local control in an emergency.

Similarly Load Shedding needs to be controlled at Level 1 until Level 1 control is not available. At that point, Load Shedding Control needs to be implemented at Level 2.

## 7. DATA BUS REQUIREMENTS

### 7.1 Background

There are basically three major data bus topologies, namely:

- (a) Linear Bus
- (b) Ring
- (c) Star with Active Hub

In addition the following control options are possible.

- (a) Centralised Master-Slave Control eg MIL STD 1553
- (b) Distributed Control with Random Access eg Ethernet

- (c) Distributed Control with Deterministic Access eg MAP and IBM Token Ring

## **7.2 The Requirements**

The following are the principle requirements:

- Secure Communications in the presence of action damage (low vulnerability).
- Distributed Control, ie not reliant on a central control position.
- Deterministic Control; for purposes of real-time control.
- Immune to Environment, Factors such as EMI.

In addition the bus must clearly have sufficient capacity to meet the system traffic requirements.

## **7.3 Selected Data Bus**

The principle requirement is to provide a system with low vulnerability and high survivability. This is reflected by using dual redundant linear bus highways with no centralised control. Of the distributed control options the token passing ring is preferred because it offers certain control. This is particularly important for both control and surveillance, where real time performance is required.

## **8. PROPOSED CONTROL SYSTEM ARRANGEMENT**

The proposed arrangement is shown in Figure 9, of which the following are the key features of the control system:

- (a) Dedicated dual redundant data highway.
- (b) Data highway based upon Token Passing Ring, ie no central bus controller.
- (c) Communications with other major systems via bus gateway.
- (d) All surveillance and control data held at local plant controller.
- (e) Control commands from primary communicated as change data, ie increase/decrease current setting.
- (f) Multiple primary control positions available.
- (g) Each primary receives all plant surveillance data for MMI purposes.
- (h) Only the one primary in control at a given time.
- (j) Graceful control degradation with fall-off in communications.

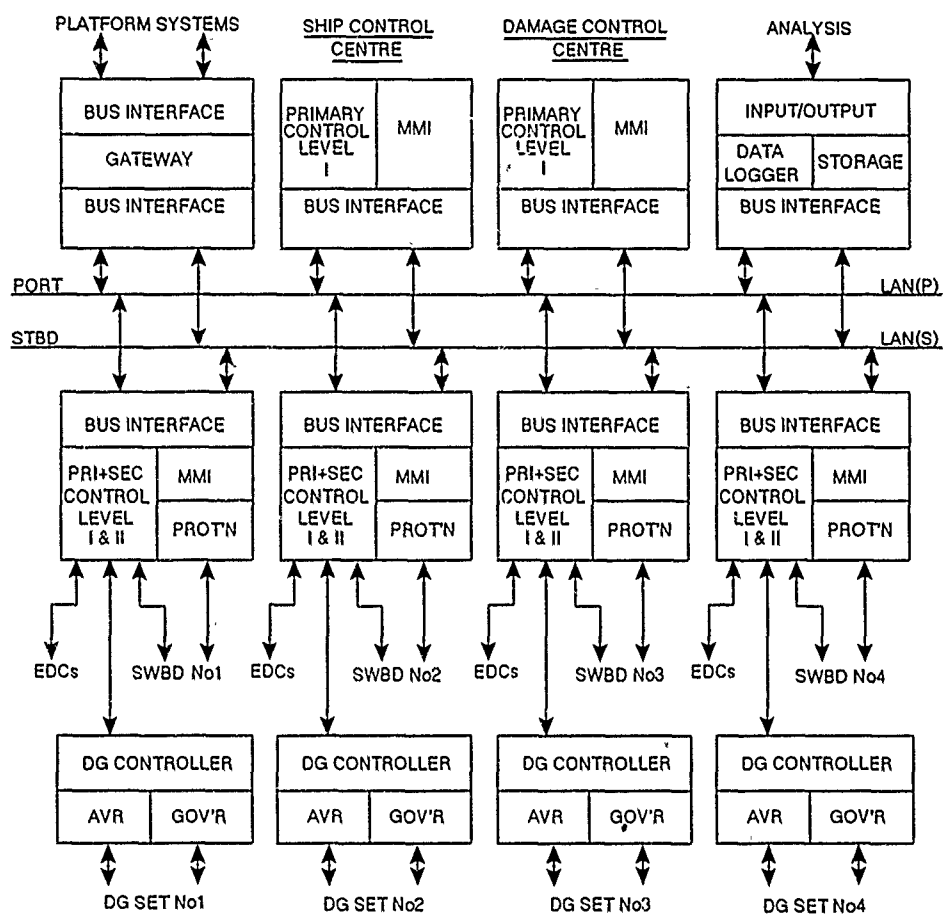


Figure 9. Automation Concept

(k) Secondary controller ensures safe operation of its power and distribution unit independent of primary control availability.

(l) System and Plant health monitoring integrated into plant/system controllers.

The control structure is based upon the following levels to ensure graceful degradation with fall-off in communications:

Primary - Central control of overall power system.

Full Secondary - Control by each secondary of its power unit on the basis of communications between all secondaries.

Secondary - Control of the single power unit by a secondary unit no communications between secondaries.

Tertiary - Control at local plant controller.

Facilities for data logging are provided by access to the data bus.

#### 9. CONCLUSIONS

This paper has presented the evolution of a warship power system design. The starting position chosen in the design loop was that of meeting the survivability/vulnerability criteria. As a result of this work a power distribution and associated control system has evolved having good fault and damage tolerance.

It has been argued, that from a management and procurement point of view, the electrical power system should be specified as a separate entity and not integrated into some large platform-wide system. On this basis a design has been proposed here incorporating a dedicated data highway. By virtue of the choice of data highway and control philosophy a failsafe design has been obtained that supports multiple primary control positions.

It should be noted that systems currently offering multiple central control, are usually based around two central processors, a plant data bus and an MMI data bus. The central processors operate together with one active and the other as a hot standby. It is our opinion that where the control philosophy presented here can be used, then the system architecture evolved here offers significant benefits over the existing techniques.

#### 10. ACKNOWLEDGEMENTS

This work has been carried out with the support of the Procurement Executive of the British Ministry of Defence.

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## FAILURE DETECTION AND CONTROL OF AN AUTOMATIC CONTROL SYSTEM IN SWATH

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### 1. ABSTRACT

With the increased reliance on automation to control surface ships, a reliable automatic failure detection and identification (FDI) is a critical first step in maintaining the integrity of the ship control systems when there is a failure in its components. Such an example can be found in SWATH vehicles where a loss of a control surface or a sensor may result in an unstable control system. A reconfigurable controller that adjusts to catastrophic changes in the vehicle dynamics would alleviate the problem, but its success depends on rapid and accurate detection and identification of the failed components. A review of existing methods for detecting system failures is given, and an alternate formulation of the solution is proposed. An example using the failure detection method presented here in conjunction with a reconfigurable control system will be given for SWATH and its applicability demonstrated under a partial catastrophic failure in the control system.

### 2. INTRODUCTION

The need for a reliable automatic control system has become increasingly more important with the expanded use of automation to improve surface ship performances. The first step in the design of a highly reliable fault-tolerant control system is the rapid detection and identification of failures in the system so that through either hardware redundancy or software adaptation, the control system can be reconfigured to accommodate the failures. Such an example can be found in SWATH vehicles where a loss of a control surface or a sensor may result in an unstable control system. A reconfigurable controller that adjusts to catastrophic changes in the vehicle dynamics would alleviate the problem, but its success depends on rapid and accurate detection and identification of the failed components.

Much has been written on the subject of failure detection and identification [1,2,3,5,6,9]. An insightful paper on the meaning and definitions of various types failures, and an overview of several failure detection methods are given by Ware in [6]. And an extensive survey of design

methods for failure detection is given in [9]. In this paper, the emphasis will be on investigating a particular approach to failure detection system that is based on generating failure identifiable residuals from an observer incorporated closed loop control system. The original work on this approach is given by Beard and Jones [10,11], and alternate interpretations and variations of their work can be found in [1,2,5]. This paper presents an alternative time domain approach to the observer based failure detection system that yields a simple design procedures for special cases.

### 3. PROBLEM FORMULATION

A failure detection and identification system typically consists of two stages: the first stage is the residual generation and the second stage is the decision making based on the residuals. A reconfigurable control system then uses these informations to reconfigure the controller to adapt to the new system configuration. A schematic of failure reconfigurable feedback system is shown in figure 1. As shown in the figure, the observer/residual generator serves the dual purpose of generating estimated states for the controller and residuals for the failure detection/identification system. The observer is designed such that when there are no failures in the system ( $f=0$ ), then the residual ( $r$ ) is zero or near zero; when there is a failure ( $f \neq 0$ ), the residual  $r$  takes on a value that uniquely identifies the failed component.

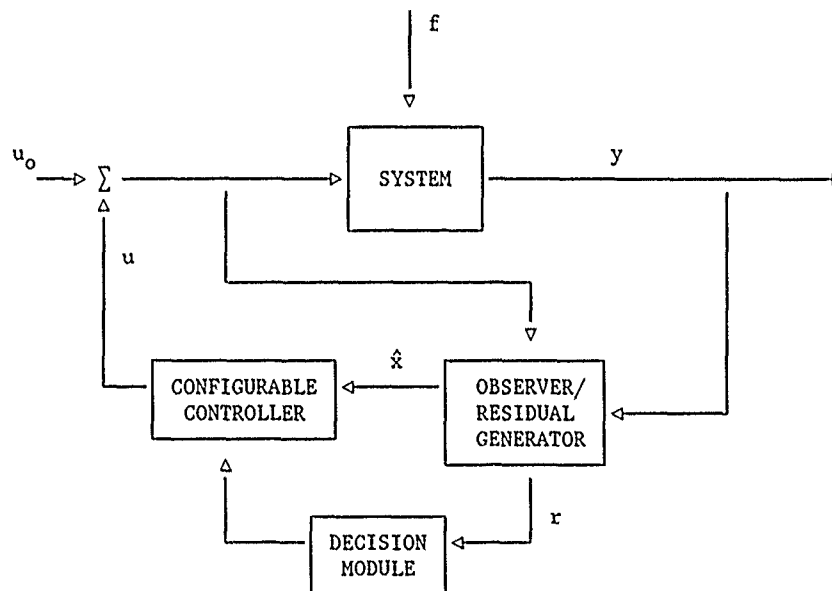


Figure 1. A schematic of a failure reconfigurable feedback system.

The mathematical formulation of the FDI problem is as follows:

Consider a linear time invariant system

$$\dot{x}/dt = Ax + Bu + Lf \quad (1a)$$

$$y = Cx \quad (1b)$$

with an associated state observer of the form

$$d\hat{x}/dt = (A+DC)\hat{x} - Dy + Bu \quad (2)$$

where  $x$  is the system state,  $u$  is the control,  $f$  is a system failure vector,  $y$  is the output,  $\hat{x}$  is the estimated state, and  $D$  is the observer gain matrix.

Define an error vector "e" and a residual vector "r" as follows

$$e = \hat{x} - x \quad (3a)$$

$$r = C\hat{x} - y \quad (3b)$$

The differential equations governing the error states "e" are then given by

$$\begin{aligned} de/dt &= d\hat{x}/dt - dx/dt \\ &= (A+DC)e - Lf \end{aligned} \quad (4a)$$

with an associated residual vector  $r$  given by

$$\begin{aligned} r &= C\hat{x} - y \\ &= Ce \end{aligned} \quad (4b)$$

The residual generation part of the FDI problem is to find a  $D$  such that  $f \neq 0$  yields an identifiable signatures on the residual  $r$ .

#### 4. A SOLUTION TO THE PROBLEM

Let  $U = [u_1, \dots, u_n]$  and  $V = [v_1, \dots, v_n]$  be such that

$$(A+DC)v_i = s_i v_i \quad (5a)$$

$$u_i^T (A+DC) = s_i u_i^T \quad (5b)$$

$$U^T V = I \quad (5c)$$

$$s_i \neq s_j \text{ for } i \neq j \quad (5d)$$

Introduce a new set of variables  $q$ ,  $e = Vq$ , and substitute into equation 4:

$$Vdq/dt = (A+DC)Vq - Lf \quad (6)$$

or

$$\begin{aligned} dq/dt &= V^{-1}(A+DC)Vq - V^{-1}Lf \\ &= \text{diag}(s_1, \dots, s_n)q - U^T Lf \end{aligned} \quad (7)$$

Assuming zero initial conditions, the solution to equation (7) is given by

$$q_{ij}(t) = \int_0^t \exp(s_i(t-\tau)) u_i^T \ell_j f_j(\tau) d\tau \quad (8)$$

where the index "i" corresponds to the i-th element of  $q$ , and index "j" corresponds to the response due to the j-th element of  $f$ . The error vector "e" is then given by,

$$e = \sum_j e_j \quad (9a)$$

$$\begin{aligned} e_j &= V^* q_j \\ &= \sum_i v_i^* q_{ij} \\ &= \sum_i v_i u_i^T \ell_j \int_0^t \exp(s_i(t-\tau)) f_j(\tau) d\tau \end{aligned} \quad (9b)$$

and the residual  $r$  is given by,

$$r = \sum_j r_j \quad (10a)$$

$$\begin{aligned} r_j &= Ce_j \\ &= \sum_i Cv_i u_i^T \ell_j \int_0^t \exp(s_i(t-\tau)) f_j(\tau) d\tau \end{aligned} \quad (10b)$$

for all  $f_j(t)$ ,  $t > 0$ .

The failures  $f_j$  are detectable and identifiable if there exist an observer stabilizing gain  $D$  such that the residuals  $r_j$  are "independent". That is,  $(A+DC)$  is stable and the rank of the matrix  $[r_1, \dots, r_h]$  is  $h$ , where  $h$  is the dimension of the failure vector  $f$ . The rank requirement on the residual matrix will be denoted the "Residual Separability" requirement. From equation (10b), it is seen that the residuals  $(r_j)$  are independent if  $u_i$  are such that the sets  $(Cv_i)_j$ , for which  $u_i^T \ell_j \neq 0$ , are mutually exclusive. Once the eigenvalues and the eigenvectors of the observer are selected to satisfy the stability and the residual separability requirements, it remains to find the corresponding observer gain  $D$ .

The filter gain  $D$  that corresponds to a given set of eigenvalues and eigenvectors is derived below:

Given,

Eigenvalues:  $S = \text{diag}(s_1, \dots, s_n)$ ,  $s_i \neq s_j$  for  $i \neq j$

and

Left Eigenvectors:  $U = \{u_1, \dots, u_n\}$ ,

The right eigenvectors are computed from equation (5c) to be,

$$v = (U^T)^{-1} \quad (11)$$

and the corresponding eigenvalue/eigenvector equation is,

$$(A+DC)V = VS \quad (12)$$

If  $\text{Rank}(CV)=n$ , then there are as many unknowns as equations and one can solve for  $D$  as follows,

$$D = (VS - AV)(CV)^{-1} \quad (13)$$

Thus, all the eigenvalues and eigenvectors can be specified arbitrarily and a solution to the Failure Detection and Identification problem exist.

If  $\text{Rank}(CV)<n$ , however, restrictions need to be placed on the allowable eigenvectors to be able to solve for a corresponding gain matrix  $D$  (see reference 4). The solvability of the Failure Detection and Identification problem then depends on the requirement that the eigenvectors that satisfy the residual separability requirement also satisfy the restrictions placed on the allowable eigenvectors.

The eigenvalue/eigenvector assignment results from reference (4) is restated here:

For each eigenvalue  $s$ , form

$$\Lambda_s = [sI - A^T, C^T] \quad (14)$$

and a compatibly partitioned matrix

$$\mathcal{O}_s = \begin{bmatrix} N_s \\ M_s \end{bmatrix} \quad (15)$$

whose columns constitute a basis for the kernel of  $\Lambda_s$ . Then,

*Proposition 1* (reference 4): Let  $\{s_i, i \in n\}$  be a self conjugate set of distinct complex numbers. There exists a matrix  $D$  of real numbers such that  $(A^T + C^T D^T)u_i = s_i u_i, i \in n$ , if and only if the following three conditions are satisfied for  $i \in n$ .

- (1) Vectors  $u_i$  are linearly independent
- (2)  $u_i = u_j^*$  whenever  $s_i = s_j^*$  (complex conjugate pairs)
- (3)  $u_i \in \text{span}(N_s)$ .

Furthermore, if  $D$  exists and columns of  $C^T$  are linearly independent, then  $D$  is unique and given by

$$D = \{[w_1, \dots, w_n] * [u_1, \dots, u_n]^{-1}\}^T \quad (16a)$$

$$w_i = -M_{si}k_i, \quad (16b)$$

$$u_i = N_{si}k_i \quad (16c)$$

## 5. EXAMPLES

### Example 1: Failure Detection Residual Generation.

A linearized equations of motion for a SWATH like vehicle given in reference [7,8] is used in this example with modifications to include the controller failure model. It is described by the following differential equations for the system states

$$\begin{aligned} dx/dt &= Ax + Bu + Lf + Gw \\ y &= Cx + h \\ u &= K\hat{x} \end{aligned}$$

with a state observer of the form

$$d\hat{x}/dt = (A+DC)\hat{x} - Dy + Bu$$

Where, the system states are

$$\underline{x} = \begin{bmatrix} x1 \\ x2 \\ x3 \\ x4 \end{bmatrix} = \begin{bmatrix} \text{depth} \\ \text{pitch} \\ \text{depth rate} \\ \text{pitch rate} \end{bmatrix}$$

the controller failures are given by the failure vector  $f$ , and the system disturbance and sensor noises are given by  $w$  and  $v$  respectively. The relevant system matrices for the above system are given below.

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -8.921E-3 & -3.574E-2 & -4.277E-2 & -5.750 \\ 0 & 7.301E-3 & 1.441E-3 & -1.377E-1 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ -7.279E-2 & -6.064E-2 \\ -3.487E-3 & 2.343E-3 \end{bmatrix}$$

$$L = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ -7.279E-2 & -6.064E-2 \\ -3.487E-3 & 2.343E-3 \end{bmatrix}$$

$$G = \begin{bmatrix} 0.0 \\ 0.0 \\ 1.0 \\ 0.0 \end{bmatrix}$$

$$C = \begin{bmatrix} 1.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 1.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 1.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 1.0 \end{bmatrix}$$

$$K = \begin{bmatrix} -5.976E-2 & 4.049E+0 & -1.026E+0 & 5.569E+1 \\ 1.330E-1 & -1.019E+1 & 7.534E-2 & -4.907E+1 \end{bmatrix}$$

Note that the failure input matrix L is equal to the control input matrix B. Thus, the failure vector f denotes the modifications to the control signal u due to failure in the controller, and the actual effective control signals to the control planes are given by the sum of u and f.

#### SOLUTION:

The eigenvalues of the observer/residual generator were chosen to have the following values:

$$\begin{aligned} s_1 &= -2.5 \\ s_2 &= -2.0 \\ s_3 &= -1.5 \\ s_4 &= -1.0 \end{aligned}$$

The first two left eigenvectors were computed from the subspace spanned by the failure input vectors  $l_1$  and  $l_2$  such that the 1-st left eigenvector  $u_1$  is orthogonal to the 2-nd failure input vector  $l_2$  and the 2-nd left eigenvector  $u_2$  is orthogonal to the 1-st failure input vector  $l_1$ . The last two left eigenvectors  $u_3$  and  $u_4$  were chosen to be orthogonal to the subspace spanned by  $u_1$  and  $u_2$  (and hence  $l_1$  and  $l_2$ ). The resulting  $u_i$  are:



$u_1$	$u_2$	$u_3$	$u_4$
0.0000E+00	0.0000E+00	1.0000E+00	0.0000E+00
0.0000E+00	0.0000E+00	0.0000E+00	1.0000E+00
3.8609E-02	-4.7850E-02	0.0000E+00	0.0000E+00
9.9925E-01	9.9885E-01	0.0000E+00	0.0000E+00

From equation (11) the corresponding filter right eigenvectors  $V$  are,

$v_1$	$v_2$	$v_3$	$v_4$
0.0000E+00	0.0000E+00	1.0000E+00	0.0000E+00
0.0000E+00	0.0000E+00	0.0000E+00	1.0000E+00
9.9885E-01	9.9925E-01	0.0000E+00	0.0000E+00
4.7850E-02	-3.8609E-02	0.0000E+00	0.0000E+00

and from equation (13) the gain matrix  $D$ ,

-1.5000E+00	0.0000E+00	-1.0000E+00	1.0831E-07
0.0000E+00	-1.0000E+00	-5.6278E-09	-1.0000E+00
8.9210E-03	3.5740E-02	-2.1805E+00	-2.7487E-02
0.0000E+00	-7.3010E-03	-1.2135E-02	-2.1391E+00

The corresponding residual directions for  $f(1)$  and  $f(2)$  failures are then,

$r_{f(1)}$	$r_{f(2)}$
0.0000E+00	0.0000E+00
0.0000E+00	0.0000E+00
9.9885E-01	9.9925E-01
4.7850E-02	-3.8609E-02

The system described above was numerically simulated for various controller failures, sensor noise, and system disturbances (see Table 1). The results are presented in figures 2 through 7 as the ratio of the third and fourth elements of the residual vectors after they were filtered by a first order filter with a time constant of 5 seconds and magnitude limited to 100. All controller failures occur at 50 seconds into the simulations. The nominal values of the ratios as computed from the above residual vectors  $r_{f(1)}$  and  $r_{f(2)}$  are 20.87 and -25.88 respectively for the first and the second controller failures. As seen from figures 2, 3 and 4, the residual generator generates expected residuals for the two controllers for all types of controller failures. In figure 2, the effect of introducing a random failure to the first controller is shown (recall that the effective control signal going to the planes are  $u+f$ ), and the ratio of the third and fourth element of the residual vector  $r$  is given to be 20.87 as expected when the failure occurs. Similarly, in figure 3 and 4, the effects of introducing a sinusoidal

and a bias failure mode to the second and first controllers, respectively, are shown, and the resulting residuals correctly predict the controller failures. In figures 5, 6, and 7, the effects of introducing system disturbances and sensor noises are shown. The failure modes in these cases simulate controller "lockup", that is, one of the control planes fails and locks in a fixed position. Although the residuals are now corrupted by noise, there is sufficient useful information in the residuals to detect controller failures.

Table 1. Test matrix for failure detection residual generation.

TEST #	System Disturbance/Sensor Noise		Controller Status/Failure Mode	
	w	h	f(1)	f(2)
1	-	-	R(0,0.1)	-
2	-	-	-	S(0.1,1.0)
3	-	-	B(0.1)	-
4	R(0,0.001)	R(0,0.001)	U(0.1)	-
5	S(0.05,1,0)	R(0,0.001)	-	U(0.1)
6	S(0.01,1,0)	R(0,0.001)	-	U(0.1)

R(m,s): Random, with Gaussian distribution (m,s - mean, standard deviation)

S(a,f,p): Sinusoidal (a,f,p - amplitude, frequency, phase)

B(m): Bias (m - magnitude)

U(m):  $-u(.) + B(m)$

Note: The effective control signals to the control planes are the sum of u and f, where the failure vector f is of the form R(m,s), S(a,f,p), B(m), or U(m) as defined above.

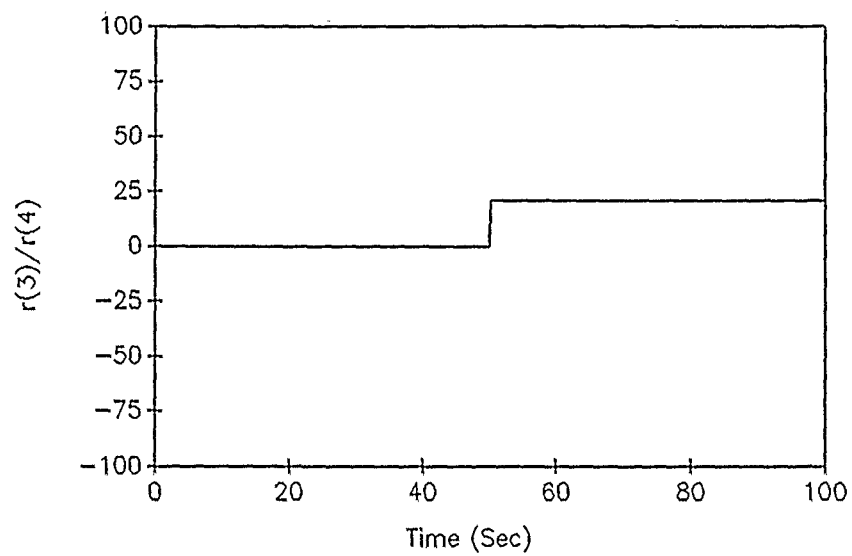


Figure 2. A plot of  $r(3)/r(4)$  for Test #1

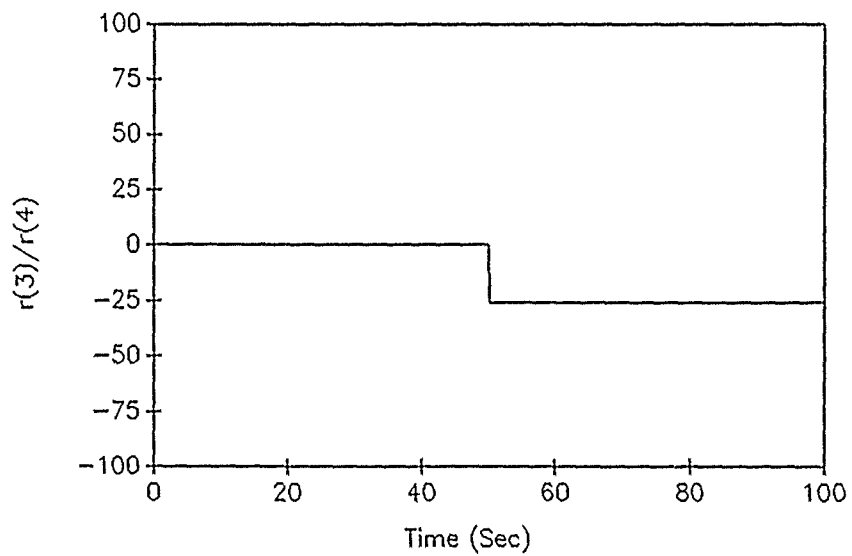


Figure 3. A plot of  $r(3)/r(4)$  for Test #2

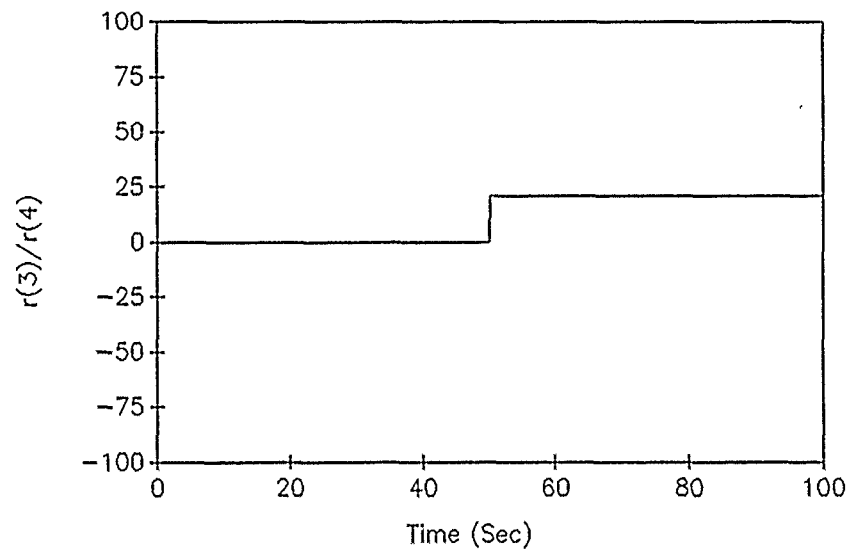


Figure 4. A plot of  $r(3)/r(4)$  for Test #3

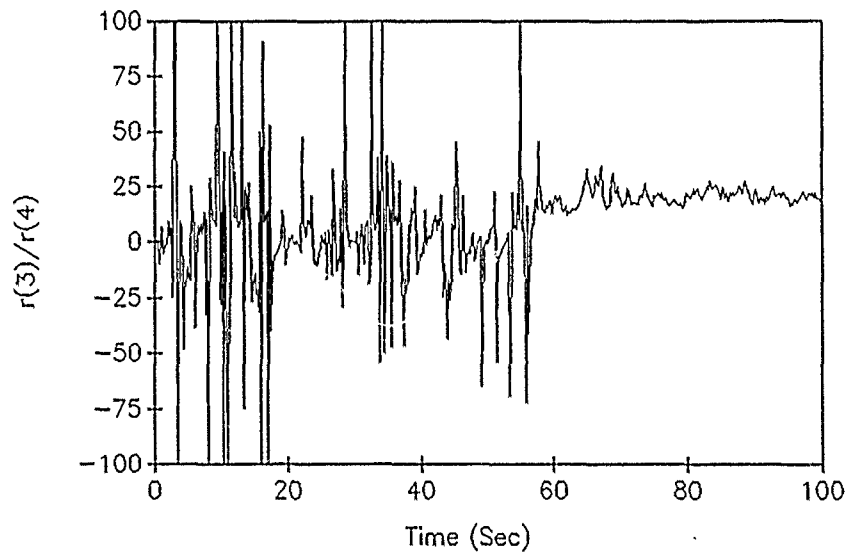


Figure 5. A plot of  $r(3)/r(4)$  for Test #4

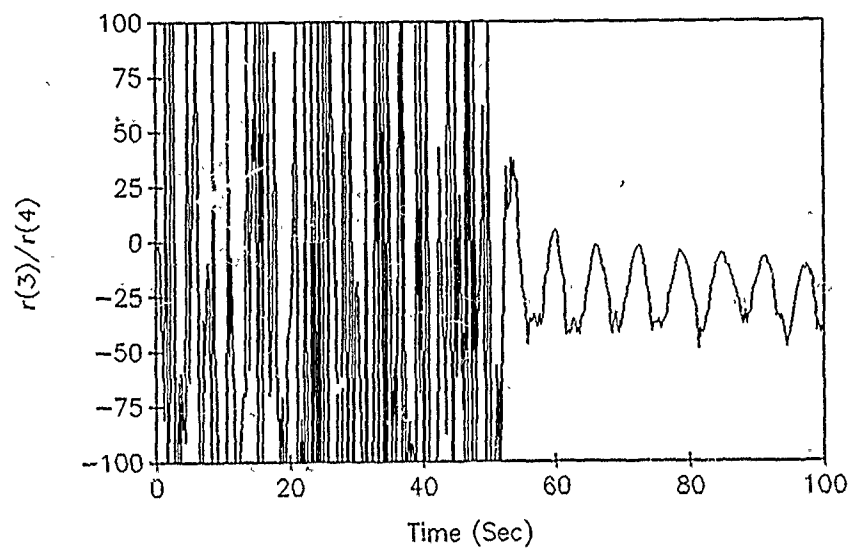


Figure 6. A plot of  $r(3)/r(4)$  for Test #5

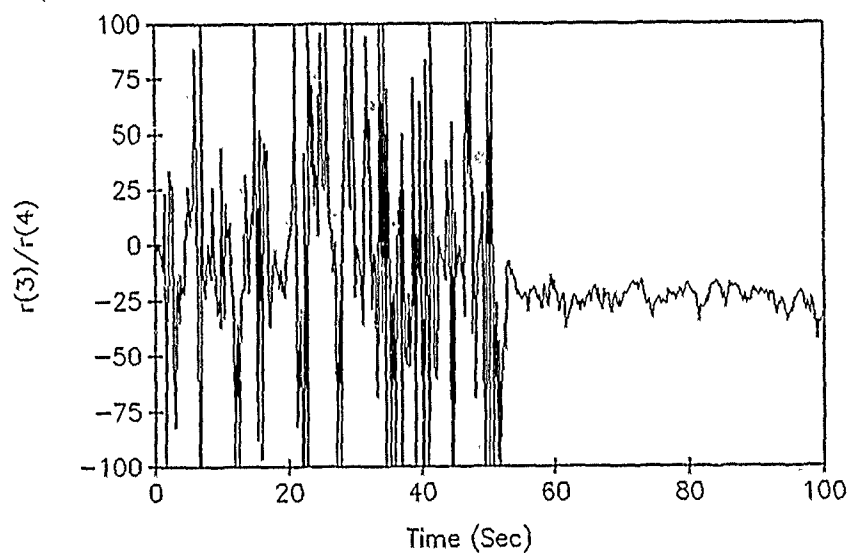


Figure 7. A plot of  $r(3)/r(4)$  for Test #6

### Example 2: FDI with Controller Reconfiguration

In this example, test #5 in Example 1 repeated for the following two cases: in the first case the system is uncompensated for the failure, in the second case the system detects failure and reconfigures the feedback controller. The following criteria is used to detect controller failures: if the ratio of the third and fourth elements of the filtered (1st order filter with 5 second time constant) residual is within +/- 10.0 of the nominal values (20.87 and -25.88 for 1st and 2nd controllers respectively) for 2 seconds, then failure is confirmed.

The controller gains for the nominal system are,

$$K1 = \begin{bmatrix} 2.906E-1 & 1.144E+1 & 2.138E+0 & -1.410E+1 \\ -9.538E-2 & -6.262E+0 & 1.148E+0 & -2.131E+1 \end{bmatrix}$$

and the system eigenvalues are,

System	Eigenvalues	
	Real	Imag
<A,B,K1>	-0.120	0.161
Both Controllers	-0.120	-0.161
Functional	-0.090	0.074
	-0.090	-0.074
<A,b1,k1>	-0.164	0.174
Failure in	-0.164	-0.174
u2	0.014	0.039
	0.014	-0.039
<A,b2,k2>	-0.164	0.174
Failure in	-0.164	-0.174
u1	0.014	0.039
	0.014	-0.039

Clearly, the system is unstable when one of the controllers is inoperative.

The gains for the reconfigured controller are,

$$K2 = \begin{bmatrix} -5.976E-2 & 4.049E+0 & -1.026E+0 & 5.569E+1 \\ 1.330E-1 & -1.019E+1 & 7.534E-2 & -4.907E+1 \end{bmatrix},$$

and the eigenvalues of the closed loop systems when one of the controllers is inoperative is as follows:

System	Eigenvalues	
	Real	Imag
$\langle A, b_1, k_2 \rangle$	-0.058	0.146
Failure in	-0.058	-0.146
u2	-0.158	0
	-0.026	0
$\langle A, b_2, k_2 \rangle$	-0.058	0.146
Failure in	-0.058	-0.146
u1	-0.158	0
	-0.026	0

The simulation results are summarized in figures 8 through 11. The failure in  $u(1)$  occurs at 50 seconds into the simulation, and the failure detection system detects the failure after 7 seconds. As can be seen from these figures, the FDI system correctly detects the controller failure and reconfigures the controller to stabilize the system.

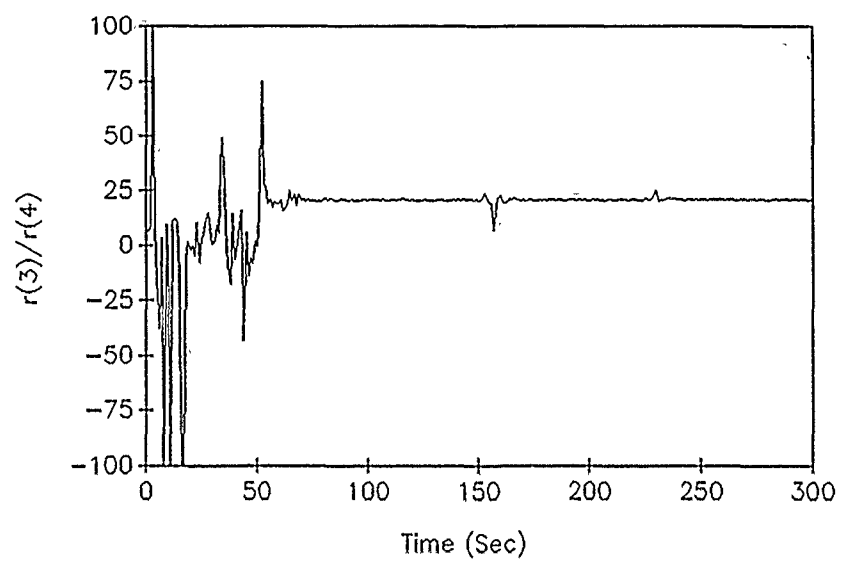


Figure 8. A plot of  $r(3)/r(4)$  for fixed controller.

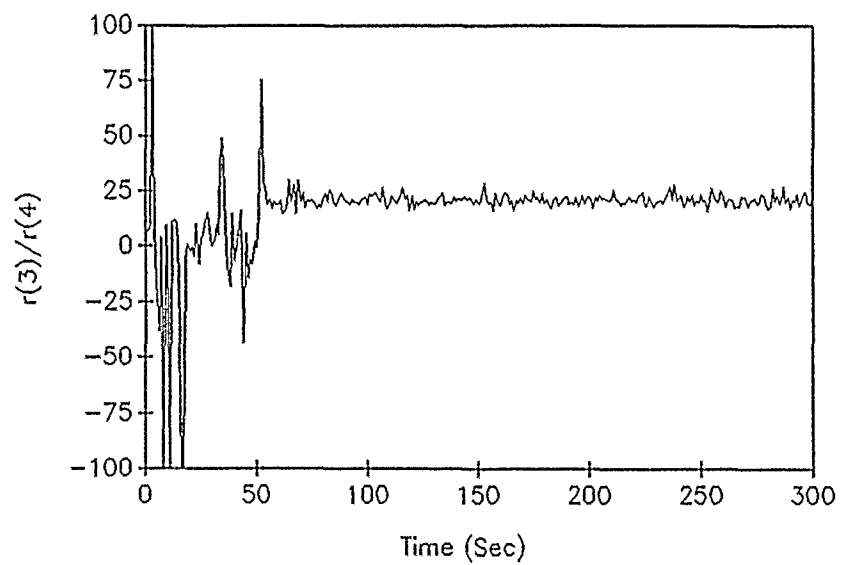


Figure 9. A plot of  $r(3)/r(4)$  for reconfigured controller.



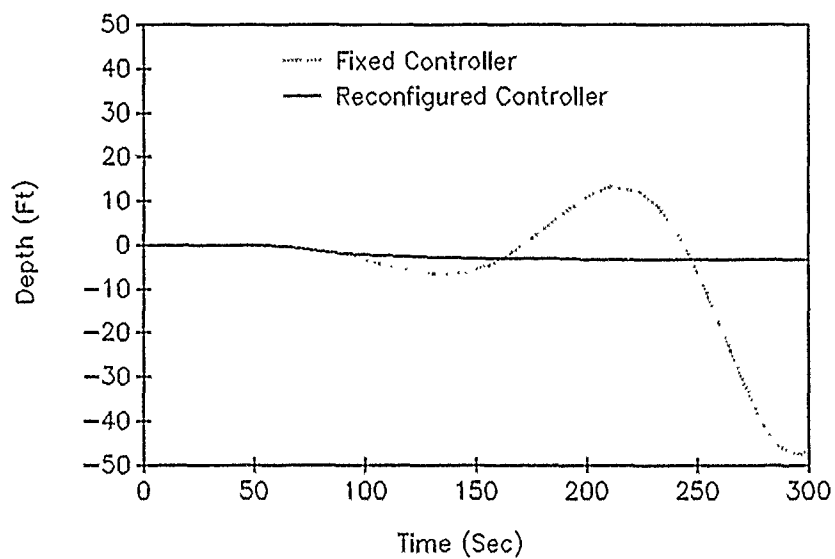


Figure 10. Depth excursions for fixed and reconfigured controllers.

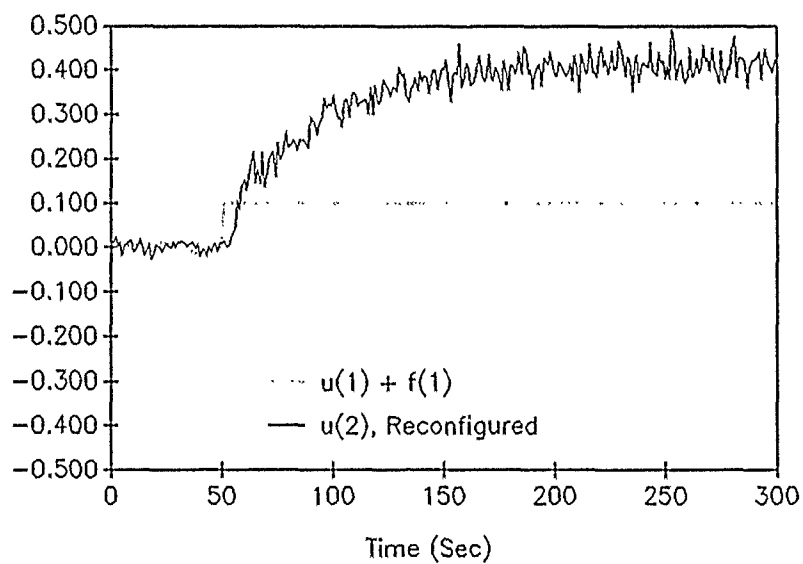


Figure 11. Effective control signals for reconfigured controller.

## 6. DISCUSSIONS/CONCLUSIONS

I have presented in this paper an alternate approach to solving the FDI problem that is based on generating residuals with signatures that identify failures in the control system. Although the example given here was limited to controller failures, sensor failures or even system failures can be cast into the form presented in this paper by appropriate augmentation of the system matrices to incorporate the failures as "pseudo-controller" failures. The solution approach given here differs from those in the literature in that a direct time domain method is used, which yields new insights into the problem and the solution. For instance, in reference [1], it is pointed out that the observer/residual generator based FDI system may suffer from sensitivity to changes in system parameters. One way in which to make the residual generator robust is by recognizing that the residuals  $r_i$  are composed of the products  $v_i u_i^T$  (see equation 10a), which are the sensitivity matrices for the observer eigenvalues [12]. Thus, by appropriate choices of the eigenvectors, the system may be made robust. Application of this method to SWATH has shown that it is an effective method for detecting and identifying controller failures, and may be used in conjunction with a reconfigurable controller to effect a robust fault-tolerant control system.

## THE SHIPS CONTROL SYSTEMS AND ELECTROMAGNETIC COMPATIBILITY

by Yoshihisa Kawamura  
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### 1. ABSTRACT

Due to a rapid and drastic advancement of the semiconductor devices , the problems of EMC , Electromagnetic compatibility is highlighted and draw attention of many engineers, especially in the fields of a digital control system , where a single surge may upset the whole system.

Various techniques are incorporated to reduce the effect of EMI , "Electromagnetic Interference" problems using past experiences and latest technology .

However , few people can really feel easy and be confident on the measures taken to prevent EMI due to the difficulties of verifying the current EMC status , especially when such tests have possibilities to damage or overstress the existing equipment such as by application of high level of simulated pulses.

This paper discusses the key principles of EMC , the procedure to identify the present EMC environments on board the ships without affecting the existing equipment and the necessary measures to prevent the EMI problems, partly referring to the grounding policy of the different groups from susceptibility point of view.

We also discuss the measures to estimate the deteriorated EMC environment.

### 2. INTRODUCTION

Modern electronic systems are discussed under the condition that appropriate EMC measures are taken on board the ships from initial ship design to final outfitting. If these conditions are not satisfied , whole systems cannot be said to be reliable. Especially a digital system with high complexity has following serious problems compared with conventional systems.

### 1) More Susceptibility to EMI

Recent rapid progress of semiconductor devices made the integration of such devices to an amount of more than one million transistors within a single chip, which is driven less than few watts.

This means that a basic logical operation in a chip is made around microwatt per transistor logic element including input and output interfacing chips, in contrast to few fraction of watt in an early days of discrete transistor logic element, as shown in Figure 1. This level of EMI signal is very common inside and outside of a control system.

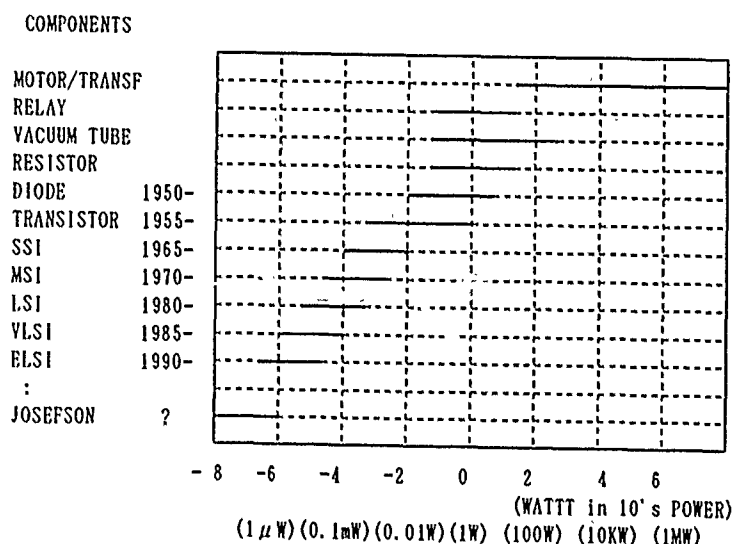


Fig. 1 OPERATING POWER PER CIRCUIT

### 2) Weakness of Digital System

From this figure we can easily estimate the vulnerability of such devices from external and internal interferences. Especially in a digital system, essentially from its operating mechanisms, is very sensitive to a impulsive type of interference, causing not only serious malfunctioning but also deterioration or destruction of the devices and eventually the system. Such trends will be more enhanced and appropriate measure should be prepared.

### 3) Difficulty to Repair

Due to the increased complexity and eventually black box trend of a digital system, repair of a equipment and recovery of the system are increasingly difficult compared to the conventional systems.

Roughly speaking, in 1950s ,major problems in control systems can be recovered by a skillful operators. In middle of 1960s, the failure can be repairable on board only by trained technicians with hours depending on the nature of a failure. In 1980s onwards ,the failure , especially that of digital sytems' can generally be repaired on board only by changing a complete printed circuit board or module. The repair made by changing piece part components may have danger of inducing another failure. In another words, consumed hours for repair not always solved the problem , rather this kinds of shipboard activities may worsen the situation.

Hence , complete and concrete measures are necessary to prevent the failure of digital electronic systems arising from EMI.

There have been three basic measures to prevent the problems from EMI, that is.

- Measure against 1) the originating sources.  
2) the propagation routes( and mechanism)  
3) the equipment suffered .

### 3. Generating Sources and Suppression Measures.

#### 1) Internal EMI Sources

There are so many sources of EMI on board ships ,which seem to be almost suppressed by appropriate measures , especially those relating to the communication ,navigation and surveillance system, even if they are handling high level of electro-magnetic energy such as high power radio transmitters , except in case of sudden and unexpected deterioration or mismatching of power output lines . However the system around electrical machineries, power generation and distribution are not fully controlled on board from EMC stand point of view. Surges normally observed in high power circuits , such as surges generated in power interrupters, motor starters and power converters are reproducible and appropriate measures are already taken to cope with such disturbances.

However, in case of grounding or short circuit on such power systems it may cause severe problems on electronic systems where unexpectedly high level of surge is generated, which is very difficult to confirm during commissioning stages.

They are sometime closely related to damage control systems of a ship where power lines are disrupted or short circuited due to heavy fightings, causing severe electromagnetic disturbances by such as a sudden change of signal and power line configuration.

Preventing measure for these troubles must be prepared more carefully in these days to verify the vulnerability and survivability with actual or simulated test on boards before commissioning using the necessary and possible measuring equipment.

## 2) External EMI Sources

There are other sources of EMI outside of a platform which may affect the operation of electronic systems. Most common items will be the thunder and atmospherics, of which sufficient measure are applied to suppress these kinds of disturbances.

The electromagnetic wave radiation from near-by ships may have sometimes caused the problem on the electronic circuit due to the ingress of microwave from such as, high power radar through hatches and windows into the compartment where electronic equipment are installed. Fraction of milliwatt out of megawatts of radar pulses has possibilities to malfunction or damage the integrated circuit of a metal oxide nature on the printed circuit boards.

There may arise more discussion on the effect of EMP, which we do not refer in this paper.

## 4. Propagation Routes and Suppression Measures

Propagation of EMI mainly routed through the interconnecting cables, of which recent progress of shielding, filtering and opto-electronics technologies solved the major problems.

In contrast to these, problems lie in the fields of grounding systems. In particular, direct current lines used in the power supply of machinery control system is normally backed up with batteries, which normally direct grounding is prohibited by some rules, making whole DC line floated from ship's hull.

In such case, these floated power lines act as propagation paths of EMI among the electronic equipment. Advent of DC/DC converter at higher output might make it easier to isolate such common linkage of EMI. In some cases, insertion of capacitors between lines and hull are very effective to improve the EMI environment, but are not welcome under the reason that these electrical charge in the capacitor may fluctuate the electrical potential between DC lines and hull.

We think that any spurious AC voltage between such lines will cause bad effect to control systems from the stand point of EMC and such level should be minimized.

#### 5. Equipment suffered from EMI and Measures to be taken.

There are enormous measures to cope with EMI on the side of disturbed equipment using filtering and shielding technics. In this paper, stress is placed on the grounding/ earthing of a frame and singal common.

There are many discussion on the procedures of grounding scheme in the fields of marine as well as industrial installation.

The ideas and principles seem to be different from Navy to Navy, between Classification Societies and various organization in industrial fields as well as grounding standards of individual manufacturers.

These societies are listed in Figure 2.

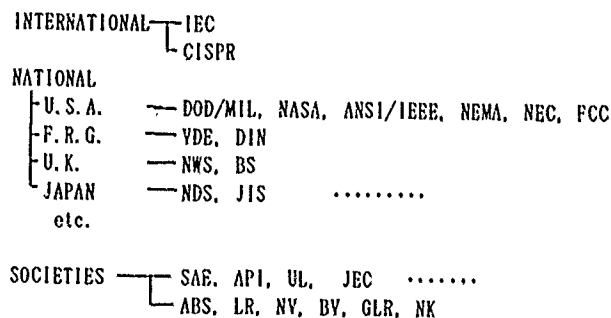


Fig. 2 ORGANIZATIONS RELATING  
EMC and GROUNDING STANDARDS

These differences have been puzzled engineers whether a signal common should be grounded or not. These rules do not always aim at EMC measures, but are sometimes pointed to the safety to human body or explosion proof measures or protection from lightning. Hence, long grounding wire is accepted so long as it has sufficient ohmic resistance picking up high level of EMI along its long line.

Our conclusion is the signal common should firmly be connected to the hull in case of ship board installation of electronic equipment.

In case, the direct grounding is not accepted as in the case of DC line or AC power lines, grounding through capacitors are recommended.

If the system is floated from ground, common mode noise appears on the circuit, which may affect the operation of circuit by the conversion of common mode to normal mode due to imbalance of the circuit through the mechanism as shown in Fig.3.

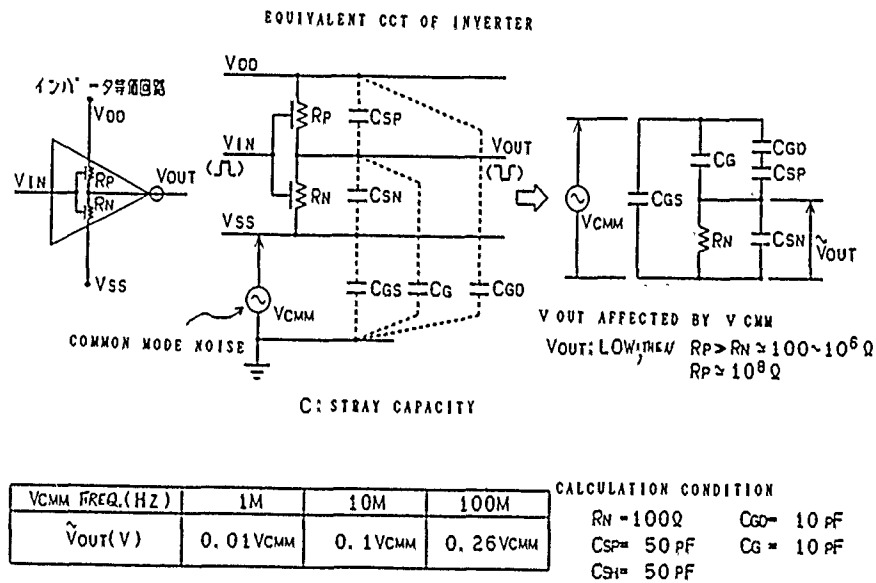


Fig.3 MALFUNCTIONING MECHANISM OF CMOS DEVICE  
DUE TO COMMON MODE NOISE



## 6. Measure against common Mode Noise

The basic way to prevent the induction and ingress of common mode noise into the circuit is to minimize the impedance between circuit and earth ground (hull) by earthing the signal common lines.

However, as we mentioned above, there are many positions on the procedures of grounding among Navies, classification societies and industrial organizations. In extreme cases, some parties prohibit to ground the signal common to the earth grounds.

In reality at industrial fields, earthing lines are not reliable as to prevent the EMC problems. (sometimes supplied from customer or other party.) However, on boards the ship, especially steel ships, hull is most reliable and can be connected easily at closest distance, whereby we can minimize the earth potential of electronic equipment as low as possible.

Some criticism are made that due to such grounding, the deterioration of insulation resistance on the power lines can not be detected at early stages. Recent progress in the electronics may solve such inconveniences easily. Grounding by high frequency capacitors may be alternative and best solution to solve the problems.

## 7. Procedure to Measure and Assess the EMC Environment

Generally speaking, it is very difficult to guarantee the safe operation of electronic equipment just observing the operating condition. There may lie the potential danger of malfunctioning or shut-down due to the EMI, generally having large dynamic range of generated level.

One way to achieve such assessment is to measure a AC and high frequency component of EMI between signal common of the equipment and hull. If the signal common is isolated by DC/DC converters, then the measurement must be made for each of the lines.

This measurement should best be made under actual operating condition. The criteria for this measurement will be around few volts from our experience and result shown in Figure 3. If it exceed 10 volts, there may be a danger of malfunctioning, which have experienced in the field. One of simplified scheme to measure such signal is shown in Figure 4. Fortunately, there begin to appear more convenient measuring sets to estimate an EMI level easily in recent commercial market.

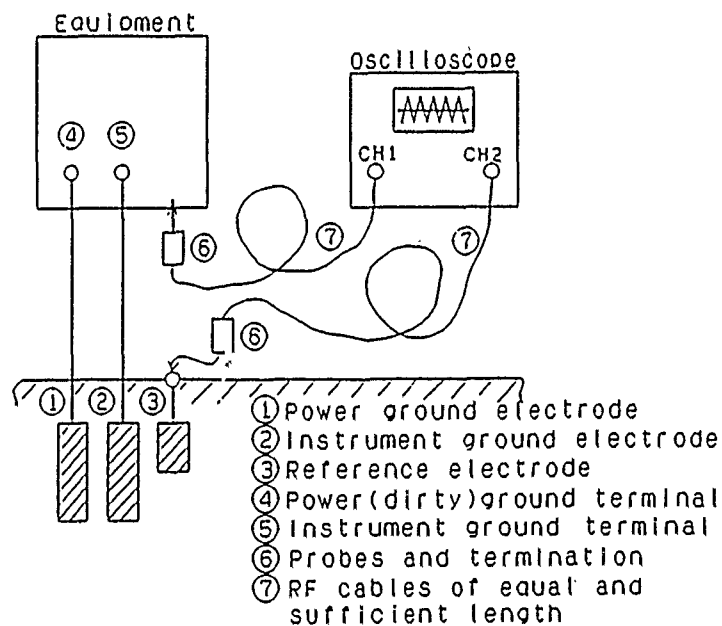


Fig. 4 EMI MEASURING METHOD

If such assessment is requested prior to the start of actual operation, impedance measurement between signal common and hull may be most effective. Typical characteristics of a signal common grounded with different length of bonding wires are shown in Figure 6.

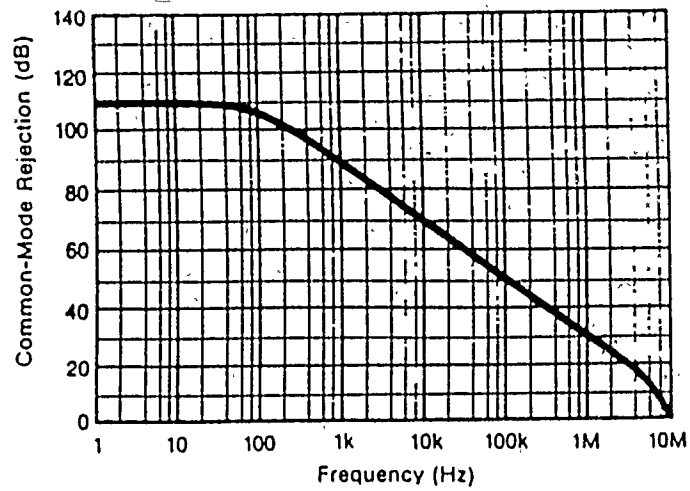


Fig. 5 DETERIORATION OF CMMR IN IC

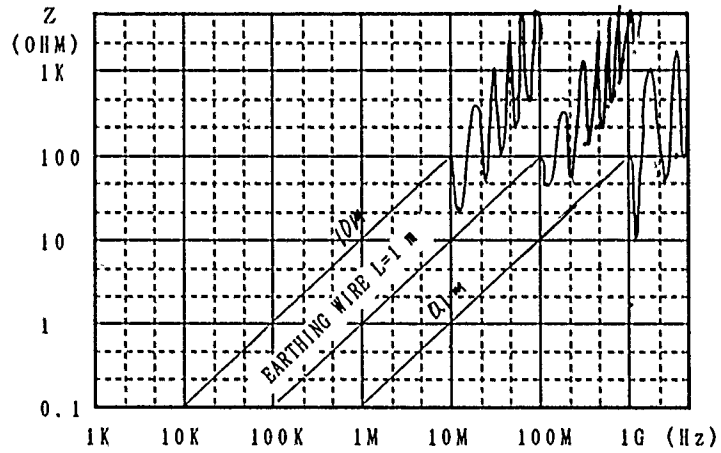


Fig. 6 IMPEDANCE OF SIGNAL COMMON TO HULL

Alternatively, injection of RF signal to the signal common line will be effective to check the EMC condition of the system. (Higher voltage may cause some trouble in the circuit.)

This is a kind of impedance measurement of signal common against hull, and can be used as an easy and useful procedure in a field to check the vulnerability of the system without utilizing specialized test set.

The frequency and applied voltage can be effective around 10 MHz and 1 volt from a radio frequency signal generator.

Example of a measuring scheme is shown in Figure 7.

Periodic measurement of this kind may help to assess the deterioration of the grounding condition, hence the EMC of the system.

#### 8. Rehabilitation EMC in Age Old Systems

To follow the recent development of electronic technology, whole or part of electronic equipment are retrofitted to the most newest models.

In such cases, analog system replaced to the digital system is most common which render the system more sensitive to the EMI.

Hence, the conversion should be made not only equipment itself and associated cables, but also the peripheral equipment such as sensors, actuators and the cable trays, cable penetrations, as well as mounting frames should be modified according to the latest standards on the EMC installation.

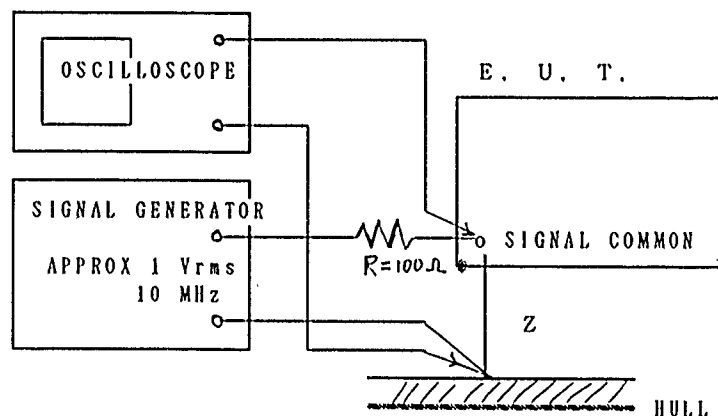


Fig. 7 SIMPLIFIED SIGNAL COMMON CHECK METHOD

One point grounding as was used in conventional systems are not appropriate for such installation and grounding must be made at as many points as possible , preferably at each cabinet. Mounting frame must be welded ,not bolted as conventional installations to say nothing of reinforcement of filtering. If welding is not appropriate, conductive compounds should be applied to the contact plane of metals.

Special attention must be payed on the power line systems. In particular, DC lines must be isolated as far as possible using DC/DC converter to achieve the isolation between the systems.

After the retrofit work is completed , quantitative data on the assessment of the EMC integrity of the system must be recorded.

#### 9. Conclusion

Progress of the electronic system is so enormous that the importance of the EMC measures will be highlighted more and more.

Particularly, on the naval vessels, EMC must be considered from not only internal sources but also from external origins such as NEMP, which is far more difficult to cope with.

Also , as a special nature of fighting ships, damage control in relationship with EMC must be considered , that is , with crippled power , communication and control system, still ship must continue to operate.

In such cases ,normal EMC environment may be destroyed and sufficient redundancy in terms of EMC must be kept to survive from such situation. Establishment of solid grounding policy for whole systems on board may be one solution to such problems.

Also, EMC measure must consider the requirement through the whole life of the ships.

## **DYNAMIC PILOTING AND ADVANCED STABILITY CONTROL**

**by Paul GINOUX DEFERMON**

**CGA-HBS**  
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### **1. INTRODUCTION**

An increasing number of ships today are using automatic systems for fixed point keeping on the bottom and straight track keeping (also on the bottom).

Dynamic piloting is also widely used today by ships of various types: minehunters, oil exploration or drilling ships, cable laying ships, oceanographic and hydrographic ships, beacon layers, diving support and rescue ships, various experimental ships, etc.

The Compagnie Générale d'Automatisme CGA-HBS offers a range of sophisticated equipment which can be produced in military technology (DAPS) or civil technology (CAPS).

The equipment is very advanced in design and technology but is at the same time reliable, rugged and very easy to use, as it is very user-friendly.

It covers a wide range, from a simple joystick to a system with triple redundancy including an integrated navigation system connected to several location sources: acoustic base, radio receiver, GPS, inertial navigation, taut wire, etc.).

### **2. OPERATING MODES**

The CAPS/DAPS family has five operating modes:

- a) Assisted Manual or JOYSTICK mode with constant heading and with change of heading.

The CAPS/DAPS can generate coordinated commands to control the longitudinal and lateral movements by action on a simple joystick. Another command is used to change the heading.

The CAPS/DAPS then optimizes load distribution between the various propulsors and rudders.

b) Course Following Mode (Automatic mode)

All the propulsors and rudders are used to follow the course and transit speed set by the operator when the ship is controlled in joystick mode with constant heading or in normal navigation mode.

c) Track Keeping (Automatic mode)

The operator defines a specific track to be followed on the bottom. The CAPS/DAPS optimizes the distance to the track and speed on the track from a reference point on the ship (sonar, moonpool, cable winch).

Through this function, the captain knows that he is accurately following the track. He therefore knows the surface scanned by the sonar for each track and can thus space the tracks at a maximum separation without requiring a large overlap due to the inaccuracy of the course followed each pass.

See Figure 1 "With dynamic pilot and without dynamic pilot".

Furthermore, this excellent tracking accuracy allows the sonar echoes already identified during previous passes to be recognized very rapidly, thereby avoiding a new classification.

See Figure 2 "Why a minehunter needs track keeping".

d) Automatic Course Following (Automatic mode)

The ship automatically follows a path consisting of 2x3 geographic waypoints entered by the operator. The CAPS/DAPS manages the propulsion system and control surfaces to move the ship successively to each of the waypoints.

e) Station Keeping above a fixed point with respect to the bottom (automatic mode).

The CAPS/DAPS controls all the propulsors and rudders to keep the ship over the selected point.

The operator himself chooses and enters the heading which the ship then keeps. To help the operator, the CAPS/DAPS computes the optimum heading considering the sea, current and wind conditions.

The CAPS/DAPS also takes other limiting conditions into account: radiated noise, operational limits of the propulsion system, tolerances on position errors.

See Figure 3 "Why a minehunter needs station keeping".

Optionally, the ship can also follow a circle with a given radius.

f) An Additional Capability: Rallying (concerns all automatic modes)

In all automatic modes, the CAPS/DAPS does not merely keep the ship on the setting. It also pilots it from the measured position to the setting following an optimum path.

Different types of paths can be used. They are customized by CGA-HBS according to the specific mission of each ship. The very special method used to make the ship follow this path to its target, called

"Rallying Method" is one of the original, sophisticated features of CAPS/DAPS. This method is the result of more than ten years of experience gained on dynamic pilots for warships.

The algorithms have gradually been improved in the successive generations of equipment.



### 3. A MODERN SYSTEM

#### Ship model :

More than a simple automatic system which corrects the error measured each measurement, the use of the ship model allows prediction of the influences of disturbances due to the wind, the current and the waves and the effect of orders given to the propulsion system to overcome the disturbances in real time. In particular, the model improves safety in at least two areas:

- Temporary sensor failures can be compensated for during the time required to resume the measurement with no significant degrading of the location accuracy.
- The data output by the sensors, essentially the position sensors, can be continuously monitored and the CAPS/DAPS computes a filtered location in real time.

The model and nonlinear techniques are used to cater for and solve problems of coupling between the three movements (longitudinal, transverse and rotation) of the ship.

More recent studies also take roll into account.

#### Technology:

In addition to the extra efficiency achieved by having teams including specialists in automatic control, hydrodynamics and software development, CGA-HBS offers state-of-the-art technology.

The CAPS/DAPS systems have an architecture including several CPUs working in parallel, providing an expandable memory capacity and fast computation time.

A library of input/output cards and the corresponding software modules allow almost all existing sensors to be interfaced while guaranteeing the necessary galvanic isolation.

#### 4. AN EXAMPLE:

The equipment of the "THETIS", experimental ship for the new series of "NARVIK" class minehunters.

On board this ship, the CAPS is connected to the following navigation equipment:

- GPS
- Inertial
- Syledis
- Compass
- Log

The CAPS controls two shaft lines equipped with fixed-blade propellers, two conventional rudders and a stern propulsor in a tunnel.

#### 5. REFERENCES AND FUTURES PROSPECTS

CGA-HBS is known in many industries for its wide range of engineers specialized in high-level automation covering both hardware and software architecture, design, production, turnkey installation. Our Servosystems Department participates in on-board applications since 1970.

The leadership is maintained at a high level, which is demonstrated by the recent placing in service of "LA FOUDRE", the new Landing Barge Transport of the French Navy.

More recently, CGA-HBS booked the following orders:

- in 1989, a CAPS 100 on the ATALANTE multipurpose oceanographic research ship.

On this ship, the CAPS is connected to a SYLEDIS radio receiver and a differential GPS.

- in 1989, a CAPS 100 for the "PROVENCE" buoy laying and servicing vessel.

- in 1989, a CAPS 100 for the "MONGE" experimental ship of the French Navy.

NOTE: From 1980 to 1985, previous generation units equipped the minehunters of the "Tripartite" program (Belgium, France, Netherlands) and the "LERICI" type minehunters produced by INTERMARINE for Malaysia and Nigeria.

The Servosystems Department is currently conducting research and development on:

- the dynamic behavior of towed vehicles
- application of CAPS to mooring assistance
- the integration of new sensors.

Benefiting from the experience gained in dynamic piloting, the Compagnie Générale d'Automatisme is now investigating tranquillization : tranquillization adds ship list and roll stability control to the functions already described.

The commands output actuate the rudders and stabilizers (fins, active tanks, etc.) of the ship in coordination.

Helicopter carrier ships and generally all ships which must be very stable are concerned by this new technique. The first application concerns the "Charles de Gaulle" nuclear aircraft carrier for which CGA-HBS was recently awarded an initial design contract. CGA-HBS was also selected to produce a simpler system designed for the new series of "LA FAYETTE" type light frigates.

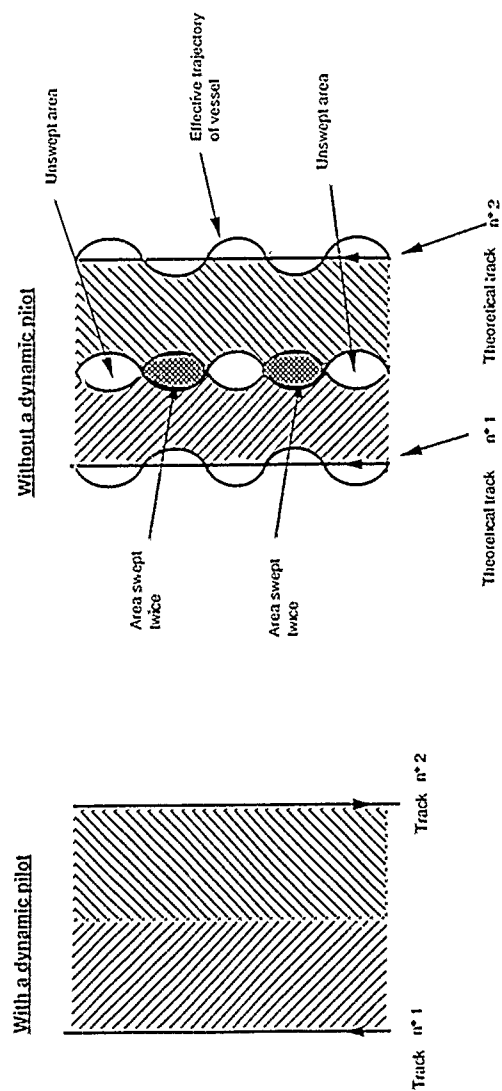
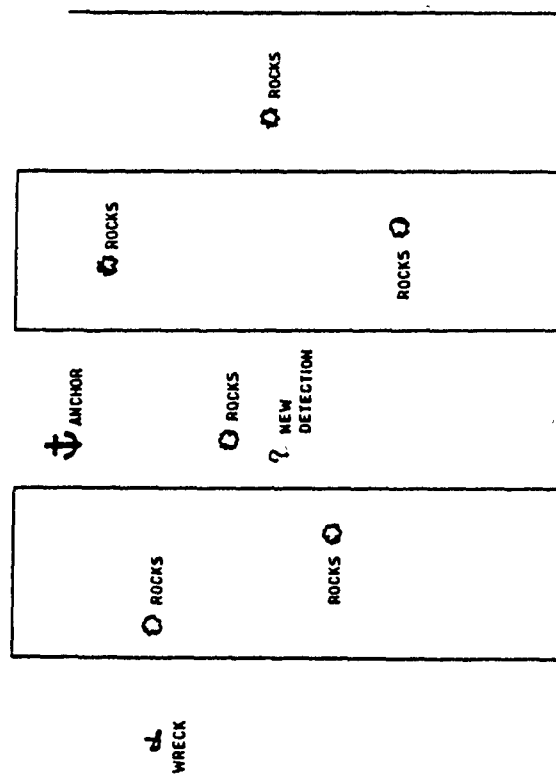
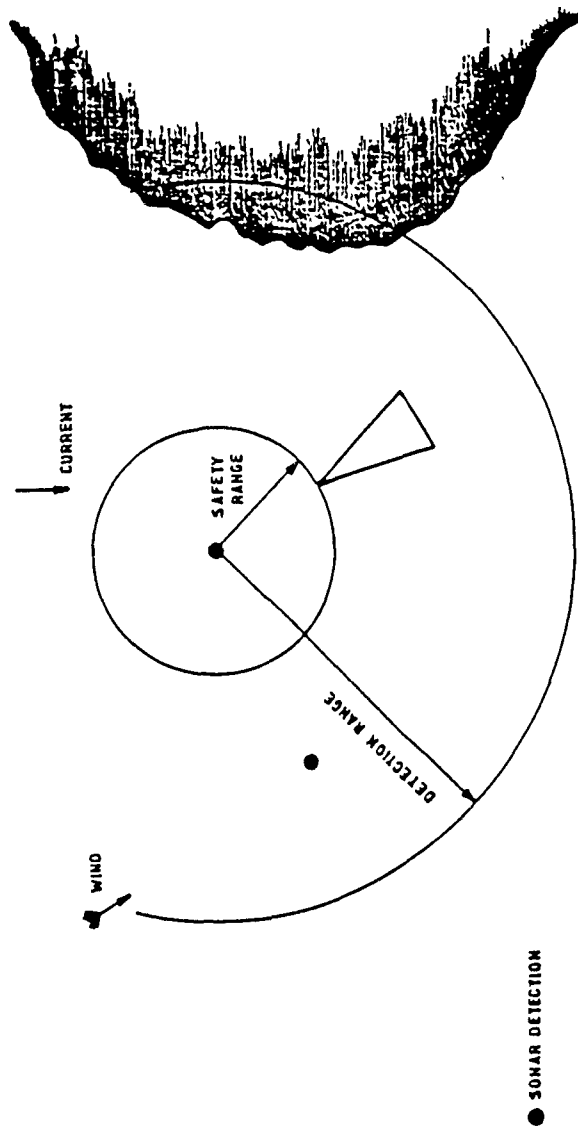


FIGURE 1



WHY A MINEHUNTER NEEDS TRACK-KEEPING

FIGURE 2



WHY A MINEHUNTER NEEDS STATION KEEPING

FIGURE 3

## RUDDER ROLL STABILISATION - A CRITICAL REVIEW

by Lieutenant Commander D C Powell MSc CEng MIMarE Royal Navy  
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### 1. INTRODUCTION

The Royal Navy has for many years used active fins in order to achieve roll stabilisation for major warships. This is not to say that other methods of stabilisation have not been employed if they have been appropriate. Examples of this are the use of controlled passive tanks in the Diving Trials Ship HMS CHALLENGER, where fins could foul diving equipments, and in the landing ship SIR GALAHAD where underwater appendages would be a distinct disadvantage. The better performance and easier installation afforded by active fins, however, has meant that it has seldom been challenged as the preferred method of roll stabilisation.

In recent years however there has been a great deal of work published advocating the use of the rudders for ship stabilisation purposes, this being generally referred to as Rudder Roll Stabilisation (RRS). The emergence of this new technique merited a reappraisal of the approach taken for warship roll reduction by the Royal Navy.

### 2. RUDDER ROLL EXPERIENCE TO DATE

Much of the early work on Rudder Roll conducted during the early 1970s (1) (2) (3) concentrated on demonstrating that the concept was feasible. The more detailed investigations that followed indicated differing opinions as to the practicality of adopting the technique. On one hand some studies (4) (5) proposed that, despite its potential, the technique suffered from instability and adverse coupling problems resulting in vessels having an increased risk of broaching and control difficulties under certain conditions. However other work, conducted principally in the USA (6), Holland (7) (8) and Sweden, has taken the opposite view that rudder roll is not only feasible but realistic. Indeed sea trials have taken place on an 'S' class frigate of the Royal Netherlands Navy, leading to the decision to specify Rudder Roll for the 'M' class frigates currently under construction. The Swedish and Danish Navies also have systems at sea in a minelayer and patrol craft respectively. These studies have argued that RRS presents a 'something for nothing' situation in that two functions are being achieved from a system previously installed to provide only one.

### 3. RUDDER ROLL APPRAISAL STUDY

In view of both the claims being made and interest shown in rudder roll, it was decided that the Royal Navy should conduct an appraisal of the technique. Since the basic concepts were not in question, the review concentrated on investigating the engineering implications of fitting a rudder roll system to a warship and to investigate the level of performance that could be achieved if such a system were adopted. Rudder roll, if accepted, would be adopted as a direct replacement for active fins, therefore throughout these studies a direct comparison was drawn between the two systems.

#### 3.1 Operational Implications

The operational implications of adopting rudder roll rest very largely on the roll reduction performance that can be achieved. This will affect all the areas listed in Table 1.

Sea keeping
. RAS
. Helicopter Operations
. Manhandling Operations
Weapon System Operation
Surveillance System Operation
(Radar, Sonar)
Crew Efficiency

Table 1: Operational Implications

#### 3.2 Engineering Implications

The engineering implication aspects investigated are listed in Table 2. The first area of concern was the design of the steering gear required for rudder roll which would have implications on its installation. It is generally acknowledged that to have any effect rudder roll requires a faster rudder slew rate than used for conventional systems, the concern being that the consequence of this would be larger hydraulic systems and higher rated motors both requiring more space and demanding more from other ship services.



Mechanical Design
Safety
Availability, Reliability, Maintainability
Cost

Table 2: Engineering Implications

A further concern, of equal importance, was that of safety. It would be totally unacceptable to compromise the levels of redundancy currently adopted for ships steering systems in order to achieve roll stabilisation from the same system.

The availability reliability and maintainability of the system has obvious implications for both system safety and cost. Concerns in this area again stem from the requirement for the high rudder slew rates causing doubts about the extent of the failure modes present. This directly affects both initial production and through-life costs.

### 3.3 Rudder Roll Performance Objectives

From the above reviews of operational and engineering implications, the performance objectives of a rudder roll system are defined as follows:

- a. To obtain acceptable performance in roll stabilisation in order that warship operational capability is not adversely affected.
- b. To obtain equivalent performance in yaw control to a dedicated steering system without compromising the levels of redundancy necessary for this essential system.
- c. To achieve the above two objectives taking due consideration of the installation constraints and support requirements which affect both unit production and through life costs.

## **4. FACTORS AFFECTING ROLL REDUCTION PERFORMANCE**

It is widely recognised that using the current steering equipment with an alternative autopilot control algorithm will not produce a system capable of meeting the roll reduction performance objective. It is therefore necessary to make changes to the design of current steering gear in order to attempt to achieve this.

The effectiveness of any roll stabilisation system is dependent upon the magnitude of the stabilisation moment that can be applied to the ship. A measure of this effectiveness is given by the ratio of the stabilisation moment to the heeling moment per degree and is known as the equivalent waveslope capacity, where waveslope capacity is defined by the following equation:

$$\gamma_s = \frac{\rho AV^2 C_L R}{1000g \overline{DGM} \sin 1^\circ}$$

where  $\gamma_s$  = equivalent waveslope capacity

$\rho$  = density of seawater

A = area of foil

V = ship speed

$C_L$  = lift coefficient

R = lever arm

D = ship displacement

$\overline{GM}$  = metacentric height

From this it is apparent that, for a given ship, the equivalent waveslope capacity, and hence stabilisation performance, can be altered by making changes to the foil area, the lever arm and the lift coefficient, which is in turn affected by the chosen aspect ratio. A comparison of typical values for a frigate and a light carrier are shown in Table 3 and a comparison of the available lever arm for both ship types is shown in Figure 1.

SHIP	RUDDER				FIN			
	FOIL AREA	ASPECT RATIO	MOMENT ARM	$\gamma_s$	FOIL AREA	ASPECT RATIO	MOMENT ARM	$\gamma_s$
LIGHT CARRIER	18.5	1.3	3.0	0.7	7.3	0.6	13.0	2.1
FRIGATE	8	1.4	2.3	1.6	5.3	0.7	7.0	3.3

Table 3: Typical values for Carrier and Frigate

One further factor, which must also be considered at this stage, is the angular slew rate of the stabilising surface. Active fin stabiliser systems typically have slew rates of around 37 degrees per second, this ensures that fin motion remains in phase with the rolling motion and also allows the fin to generate the largest possible stabilising moment as early as possible. In comparison to this rudders typically have slew rates of the order of 3 degrees per second. It is generally accepted that a slew rate of this order is inadequate for a rudder roll installation and that a faster rate is required.

## 5. POTENTIAL MEASURES TO PRODUCE AN EFFECTIVE RRS

From the above it is therefore apparent that, for an RRS system to be effective, changes in rudder and steering gear design are needed. Measures to improve aspect ratio, foil area, moment arm and slew rate are therefore discussed.

### 5.1 Aspect Ratio

The main reason for the selection of low aspect ratios for stabilisers is to ensure that stall does not occur over the range of fin operation. This results in the lift coefficient for a given angle of attack being lower than is the case for higher aspect ratios. This does not present a being problem in this case due to the high angular slew rate of the fin, which ensures that a suitable lift coefficient is achieved soon after the demand is made. In order to provide the necessary steering performance rudders use higher aspect ratios to enable high lift coefficients to be performance achieved at lower angles of attack. The stall angle in this case occurs within the operational envelope of the rudder, albeit usually within the last 25% of the range. It is therefore considered that there is more to be lost than gained in making any changes to the current selection of rudder aspect ratio.

### 5.2 Foil Area and Moment Arm

Increases in the area of the foil are also linked with the available moment arm. As was shown in Figure 1, above, the moment arm currently provided by the rudder is, at best, a factor of three lower than is achieved by a stabiliser fin. It is this aspect of rudder design that will require the most attention. Increasing the rudder moment arm can be achieved by moving the rudder centre of pressure further from the roll centre. Methods of achieving this are:

- a. Increasing the rudder outreach, or
- b. Angling the rudders outboard

Increasing rudder outreach can be achieved by increasing the rudder span, reducing the height above the baseline of the after cut-up or mounting the rudder on a skeg. The primary limitation affecting each of these options is the need to ensure that the blade does not extend beyond the ships local

beam or the keel. In addition, the latter two options will require alterations to the ship's lines near the stern which would have serious effects on ship powering and resistance and the interaction between the propeller and the hull.

Angling the rudders does provide a marginal increase in the moment arm, however the penalties in taking this option include increased risk of aeration and cavitation due to the rudders being brought closer to the surface and poorer yaw performance as the rudders are now outwith the propeller race. By far the worst penalty however is the impact that this would have on the hydraulic complexity due to the necessity, even for moderately angled rudders, to dispense with the normal mechanical linking. This would also adversely affect the steering system failure modes.

For the reasons explained above the only method of improving the available moment arm worth further consideration is that of increasing the rudder span. This will, of course, increase the bending moments in the rudder stocks and the bearing loads.

### 5.3 Rudder Slew Rate

The current values of slew rate, previously stated, indicate that fin slew rates are some twelve times larger than those of rudder systems. To increase the slew rate by this much is clearly not practical, as this would require unacceptable increases in the size of the hydraulic system and place loads on the steering gear that are unlikely to be sustainable. Therefore a compromise figure between these two extremes is necessary.

## 6. SELECTION OF SHIP PARAMETERS FOR RRS STUDY

It was therefore concluded that the only design changes which could feasibly be made to the current design of steering gear, in order to improve its RRS capacity, were to extend the rudder span and to increase the rudder slew rate. It was necessary therefore to determine the extent to which these could be altered. Since the dimensions of the rudder would affect the slew rate calculations it was necessary to determine the rudder geometry first.

As stated in the previous section, extending the span is a compromise between improved moment arm and increased risk of damage if the rudder is allowed to extend below the keel line. In practice the bottom of the propeller disc extends below the keel line and it was therefore decided that to increase the rudder span in line with the propeller would not constitute a significant additional risk. This allowed a 33% increase in the rudder span. Using this revised rudder span, computer modelling was undertaken in order to determine a suitable rudder slew rate. The modelling was undertaken for three sea states and two wave encounter angles. The results of these simulations at Figures 2 and 3 indicate that variations in encounter angles have little effect on the slew rate profiles. In all cases, roll reduction performance appears to saturate in the region of 10 degrees per second with relatively flat profiles thereafter. In order to be sure of selecting a slew

rate that was safety in the 'flat' region of the profile, and bearing in mind the reservations regarding large increase in slew rate, a rate of 15 degrees per second was chosen for the Rudder Roll study.

## 7. RUDDER ROLL SYSTEM PERFORMANCE

In order to assess RRS performance, computer simulations were carried out on mathematical models of a frigate. Two models were used, the first corresponded with that of the current ship configuration, including its active fin stabilisation system, the second included the modifications discussed in Section 6. This involved changing the rudder geometry and increasing the angular slew rate to 15 degrees per second.

Seas were modelled in the simulation program by using a Pierson-Moskowitz two parameter spectrum. This sea model produces waves of the correct height and period, and in the correct distribution for a typical North Atlantic swell. However, the waveshapes themselves are not typical, having a sharper crest and a flatter trough than is normal, although this does have the advantage of eliminating the confused sea pattern caused by the more usual short crested multi directional seas.

The simulations compared roll reduction performance achieved by both models and the rudder activity of each. These simulations were conducted at 12, 18 and 30 knots and for a number of encounter angles ranging from bow to quartering seas.

The roll reduction performance results are shown in Figures 4, 5 and 6 and indicates that, for all speeds, fin stabilisation provides greater levels of roll reduction. The performance of an RRS system is markedly less, especially in conditions of bow and quartering seas. The rudder activity results are shown in Figures 7, 8 and 9 and indicate much higher levels of rudder activity in the case of the RRS system.

## 8. ENGINEERING ASSESSMENT

The engineering assessment of rudder roll considered the design implications of fitting and operating the machinery required, the safety of such a system and the costs involved.

### 8.1 System Design

Increasing the span of the rudder has the effect of increasing the rudder weight by 25%. The torque required for this larger rudder will also depend upon the chosen slew rate. Torque curves for increasing values of slew rate are shown in Figure 10 and indicates that for the chosen slew rate of 15 degrees per second, the torque requirement will increase by 30%. This can only be achieved by increasing the dimensions of the rudder stock or by specifying an enhanced material specification, or both. Whichever method is adopted, the rudder stock bearings will experience higher loads. In addition the stock will be rotating at a higher rate. It is therefore highly likely

that improvements in bearing materials will be necessary. The largest alterations necessary, however, will be in the hydraulic system. Calculations indicate that flow rates in the order of 50 gallons per minute are necessary to achieve the slew rates required, this compares with the currently installed equipment which has a flow rate of around 20 gallons per minute. This represents a flow rate increase of some 250%, a large uprating of both the pump and motor.

### 8.2 System Safety

In order to maintain the currently specified safety requirements it has been necessary to maintain the policy of providing sufficient levels of redundancy. Whilst this does not present a problem in the case of the control system, it does have great significance in the case of the mechanical elements of the system. It has already been established that the motors, pumps and other associated equipment will be substantially larger, this will obviously impact on the necessary space requirements.

In addition to the need to include high levels of system redundancy it has also been necessary to include mechanisms in which the stabilisation mode is disabled under certain circumstances in order that the steering function is not compromised. This will increase the complexity of the control system and have repercussions for aspects of ship and weapon system operation.

### 8.3 Costs

It is difficult to draw meaningful cost comparisons between ships fitted with a tangible fin system and a ship fitted with a hypothetical rudder roll system as discussed in this paper. It would appear reasonable, however, to assume that the cost of increasing the size and complexity of the rudder system is likely to be of at least the same order as that for the procurement of a fin system.

## 9. CONCLUSIONS

This study has shown that the rudder stabilisation technique can produce worthwhile levels of roll stabilisation for frigate sized ships. Despite this, however, the performance available from such a system falls short of that currently available from fin systems.

In order to achieve the performance levels described, changes are required to both the rudder geometry and angular slew rate, with consequent increases in the required space envelope for installation.

In addition, achieving the required safety standards for the primary (steering) function compromises the availability of the secondary (stabilising) function. It has therefore been concluded that since rudder roll performance is lower than that available for fin systems, it requires changes to installation profiles, and cannot be considered to be

available in the same way as a fin system, that the Royal Navy would not consider substituting active fin stabilisation for rudder roll.

However the study has shown that for small vessels, where active fins would not have been considered and in consequence no roll stabilisation provided, that the inclusion of a rudder roll system could be considered.

Disclaimer. The views expressed in this paper are those of the author and not necessarily those of the MOD(UK).

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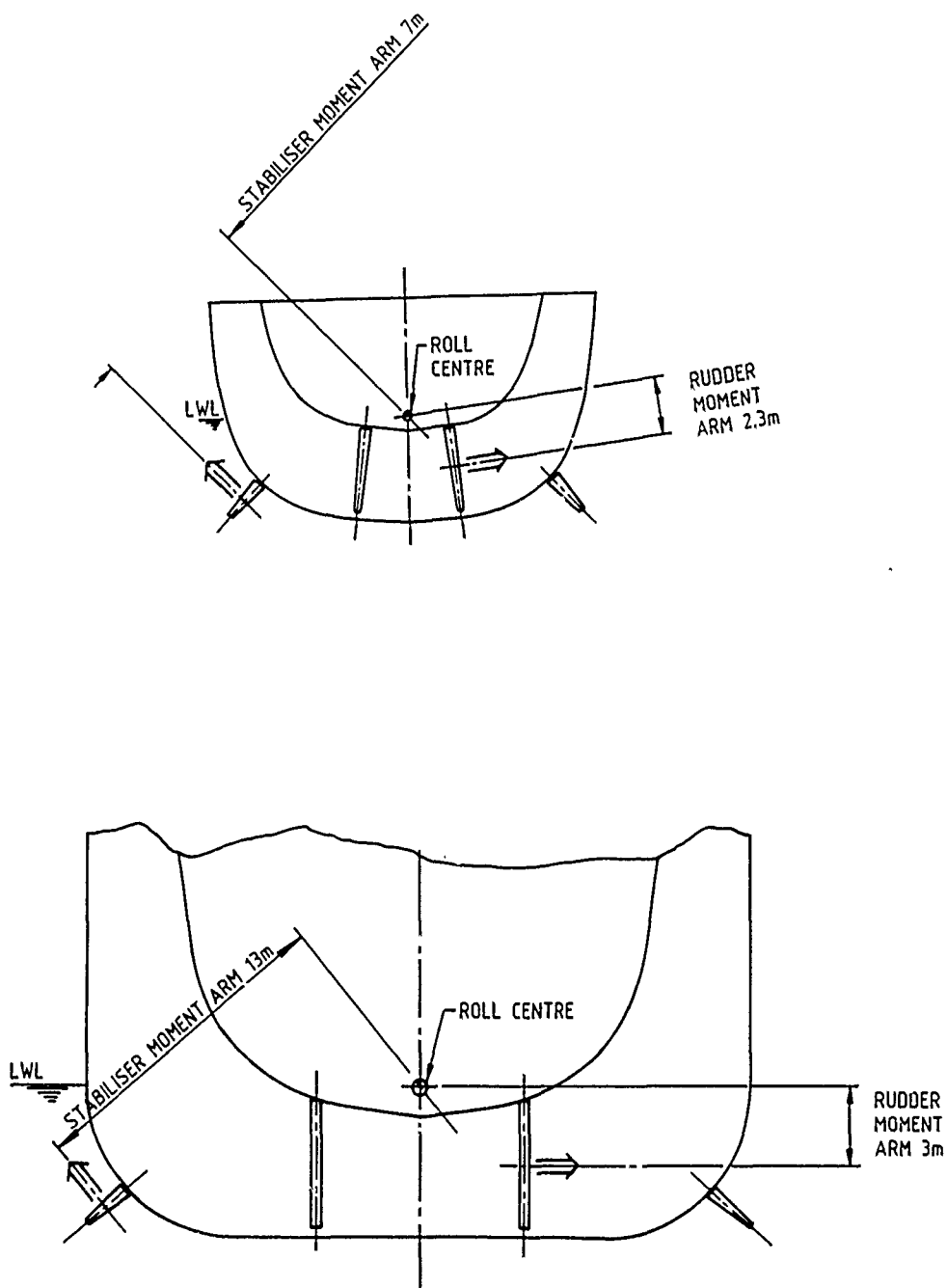


FIGURE 1 RUDDER AND STABILISER MOMENT ARMS FOR TYPICAL FRIGATE AND CARRIER

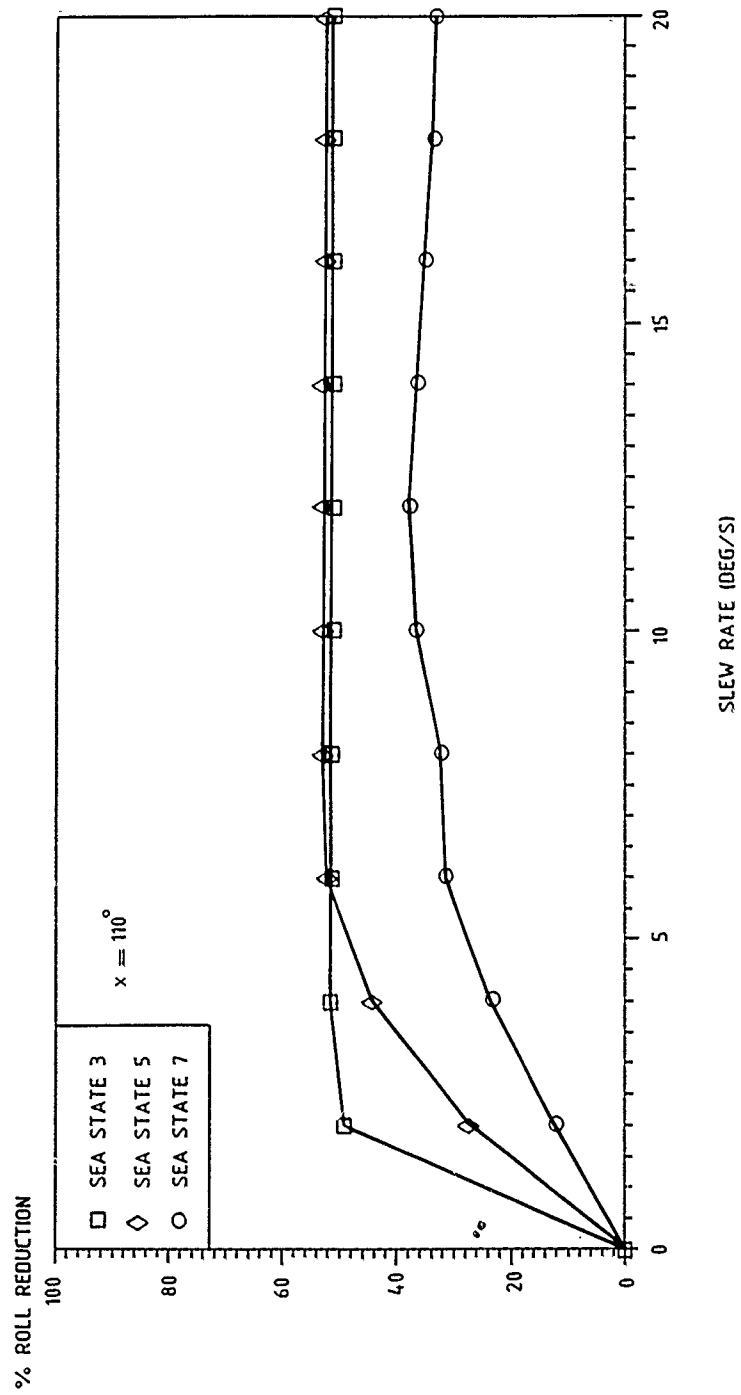


FIGURE 2 PERCENTAGE ROLL REDUCTION/SLEW RATE

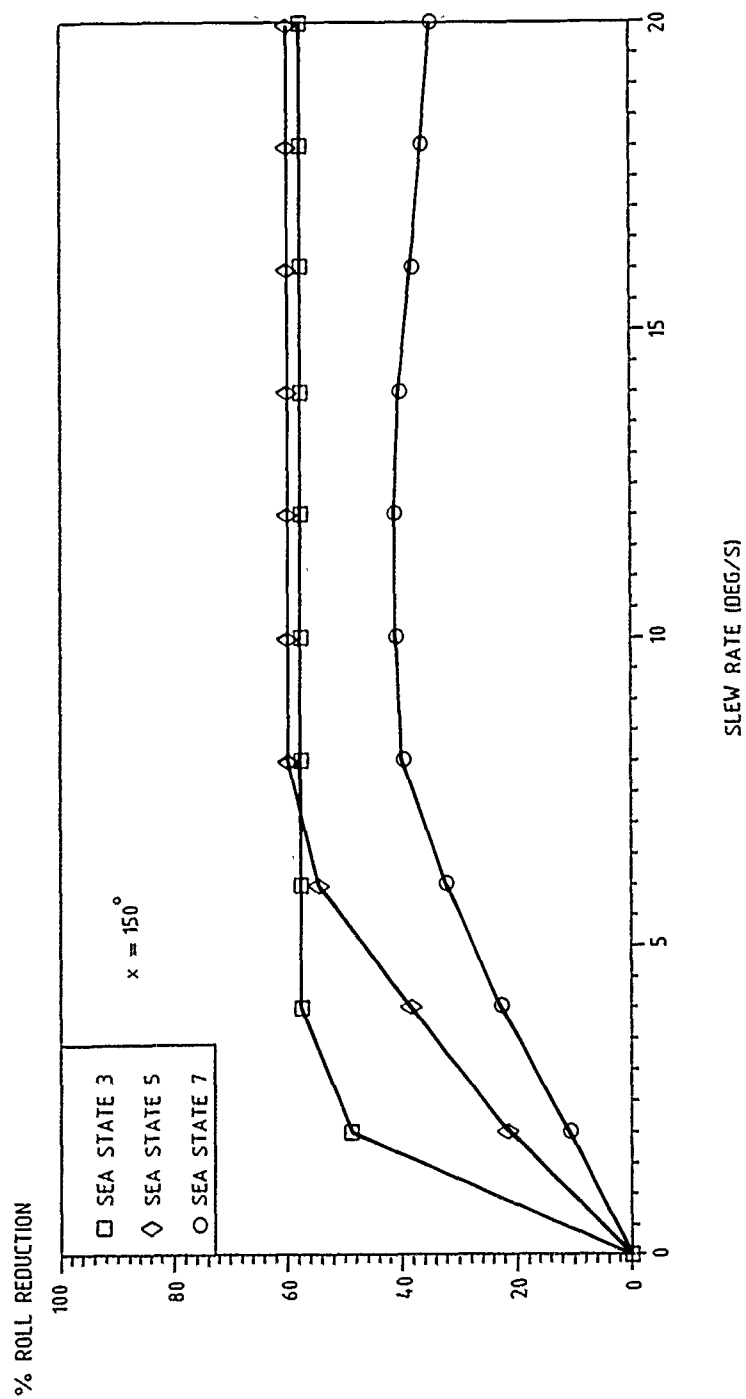


FIGURE 3 PERCENTAGE ROLL REDUCTION/SLEW RATE

X FIN STABILISED  
 □ RUDDER STABILISED

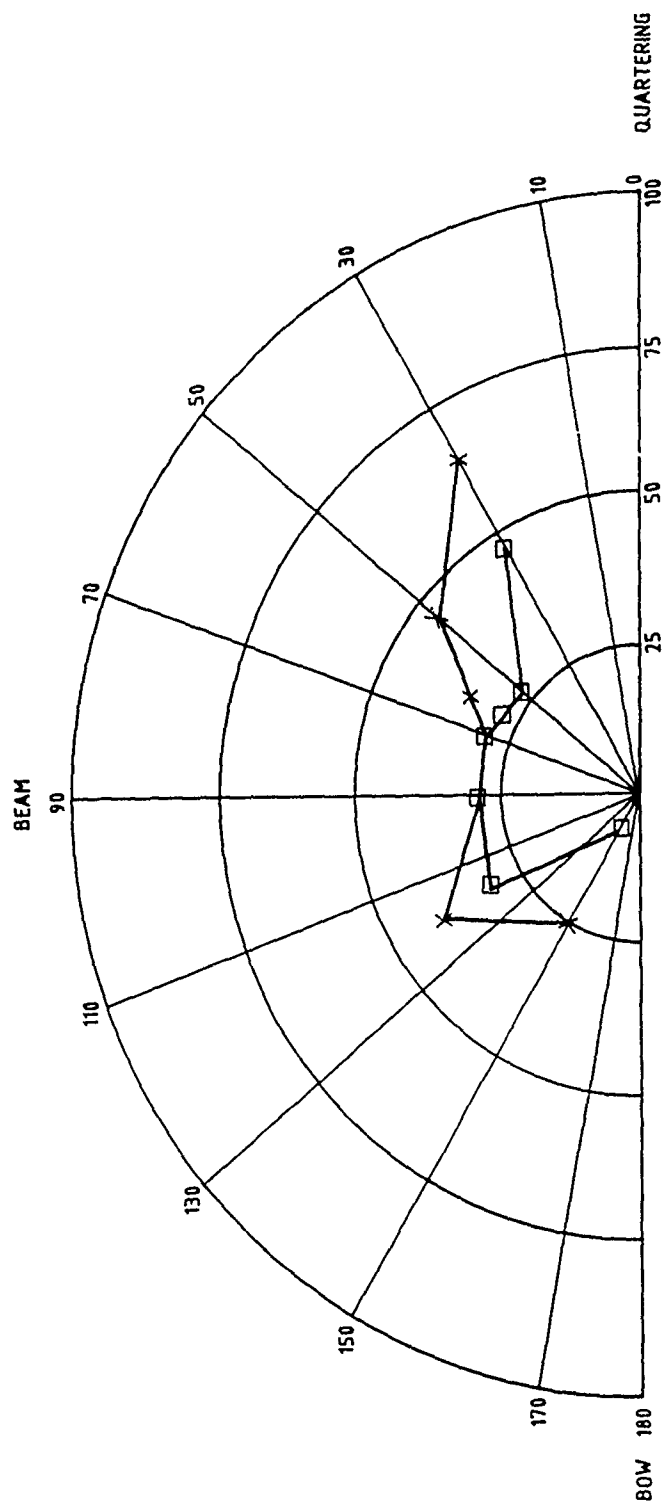


FIGURE 4 PERCENTAGE ROLL REDUCTION (12 KNOTS)

X FIN STABILISED  
 □ RUDDER STABILISED

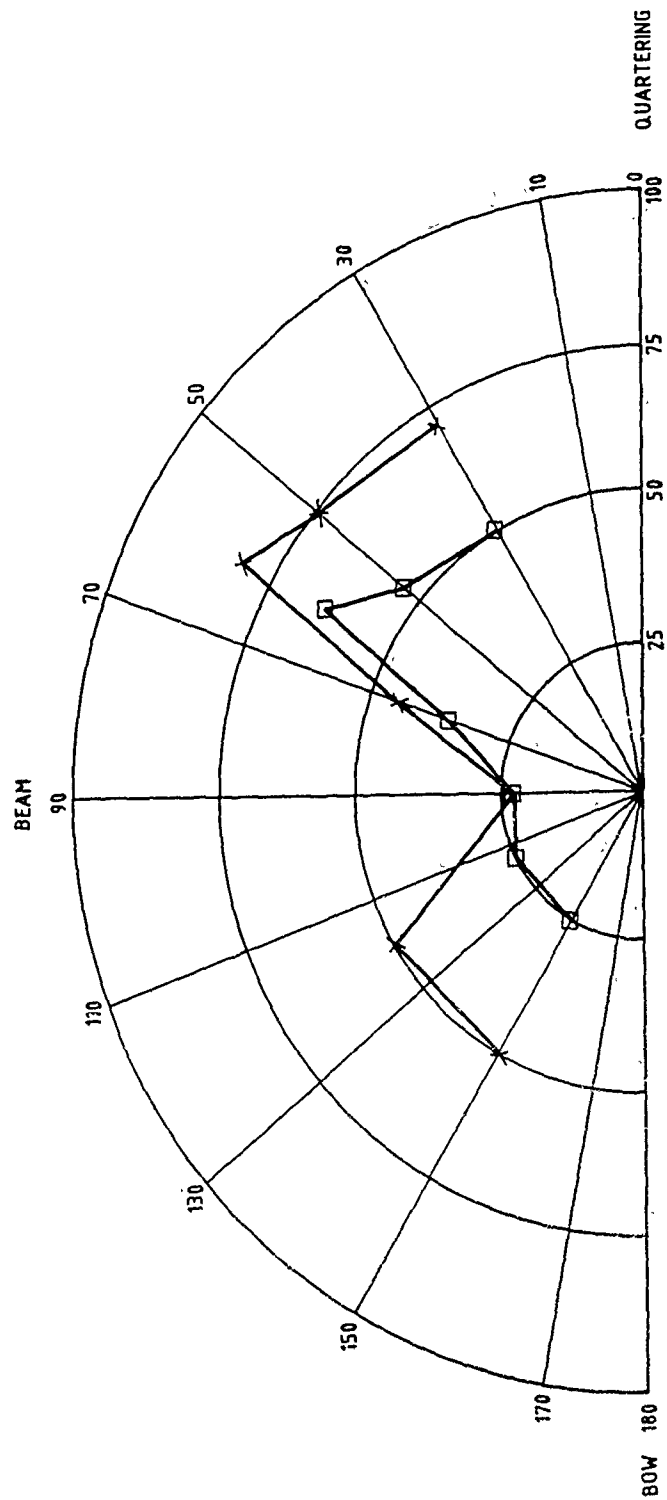


FIGURE 5 PERCENTAGE ROLL REDUCTION (18 KNOTS)

X FIN STABILISED  
 □ RUDDER STABILISED

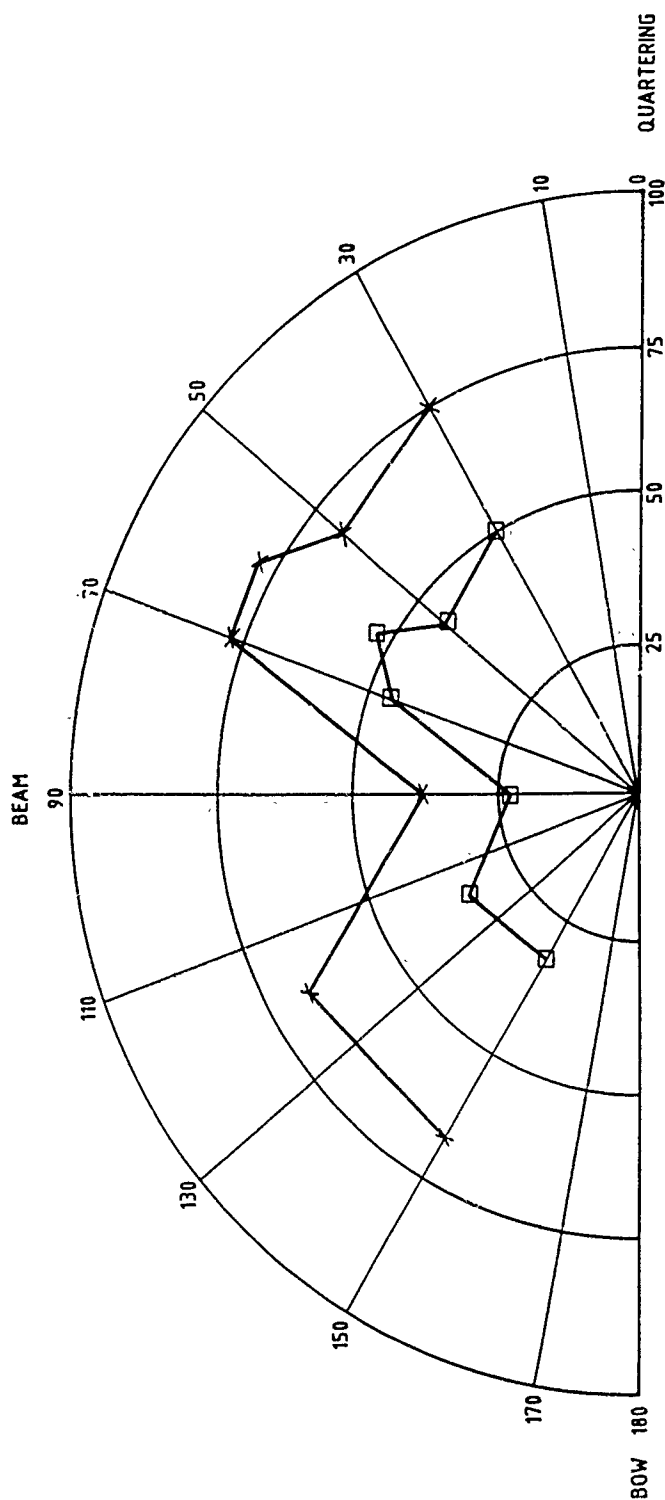


FIGURE 6 PERCENTAGE ROLL REDUCTION (30 KNOTS)

- X FIN STABILISED
- RUDDER STABILISED

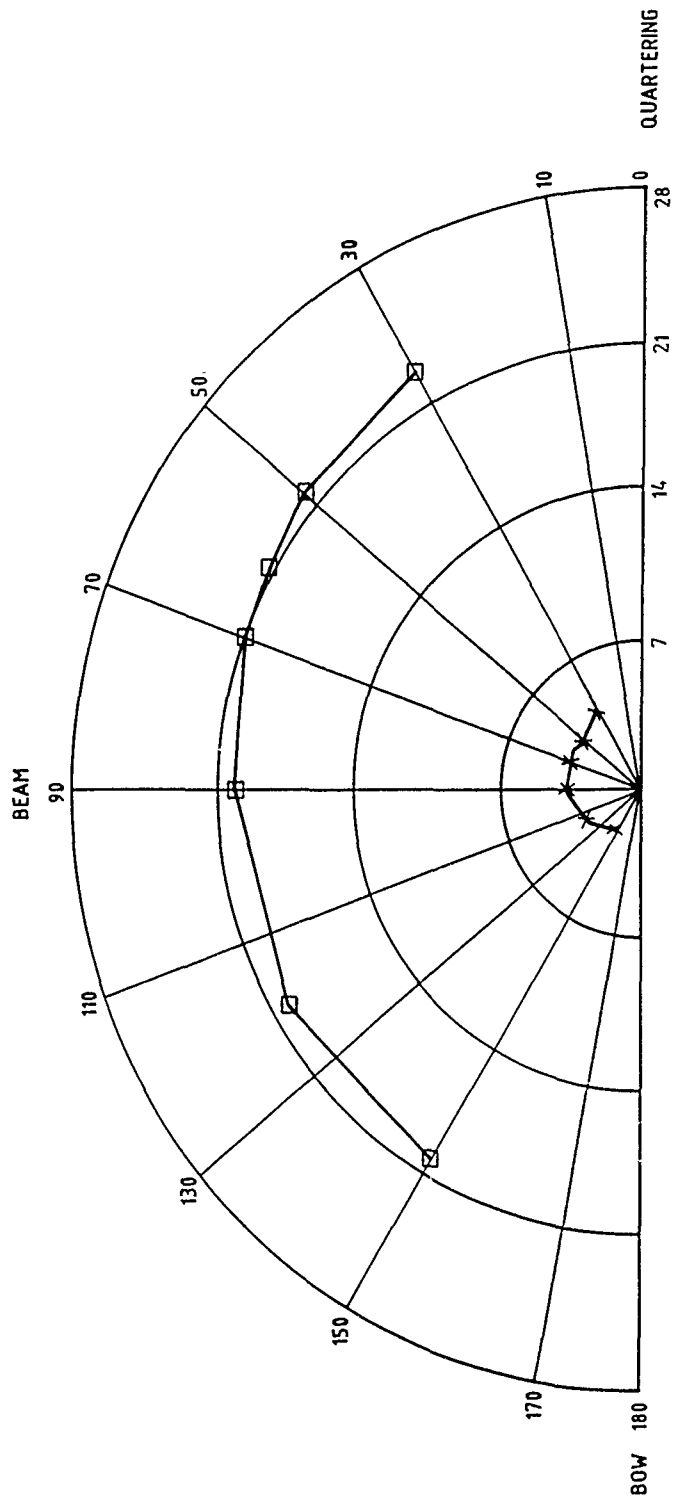


FIGURE 7 RUDDER ACTIVITY (12 KNOTS)

X FIN STABILISED.  
 □ RUDDER STABILISED.

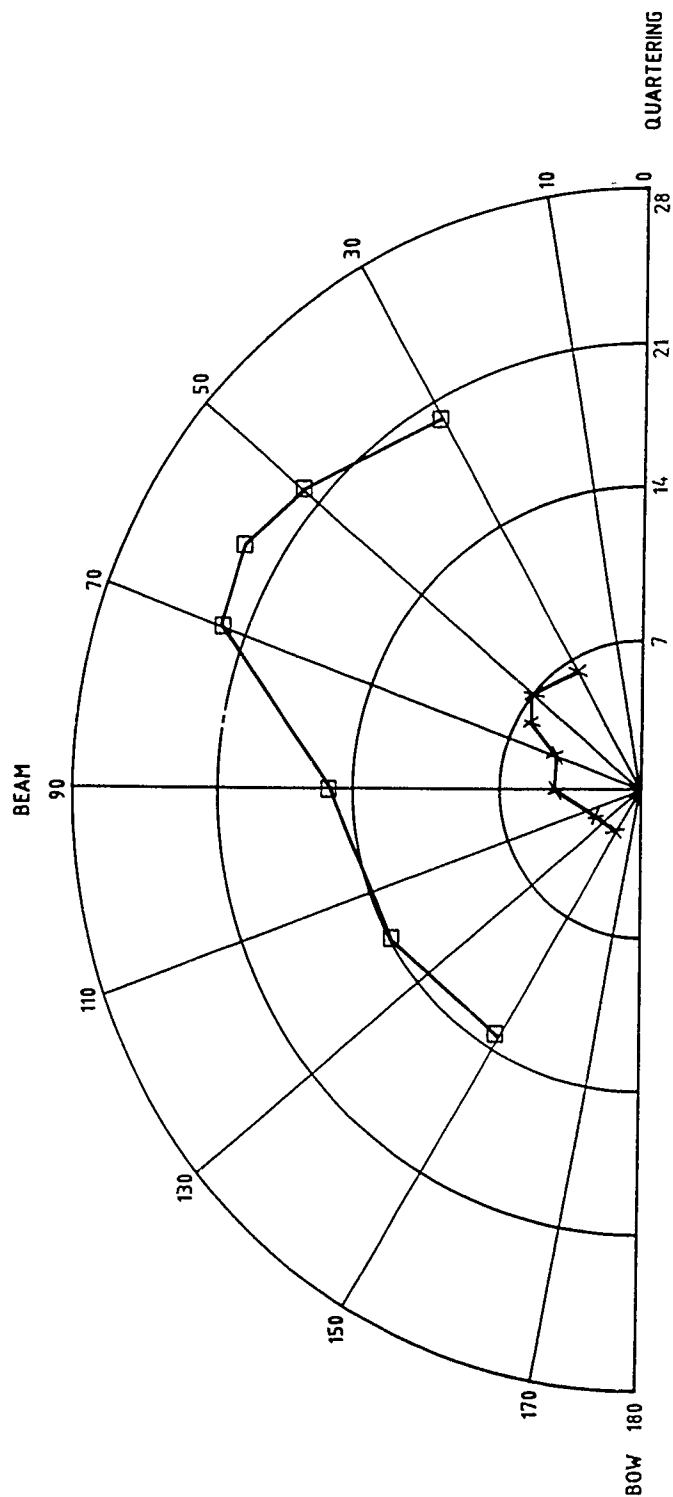


FIGURE 8 RUDDER ACTIVITY (18 KNOTS)



X: FIN STABILISED  
 □: RUDDER STABILISED

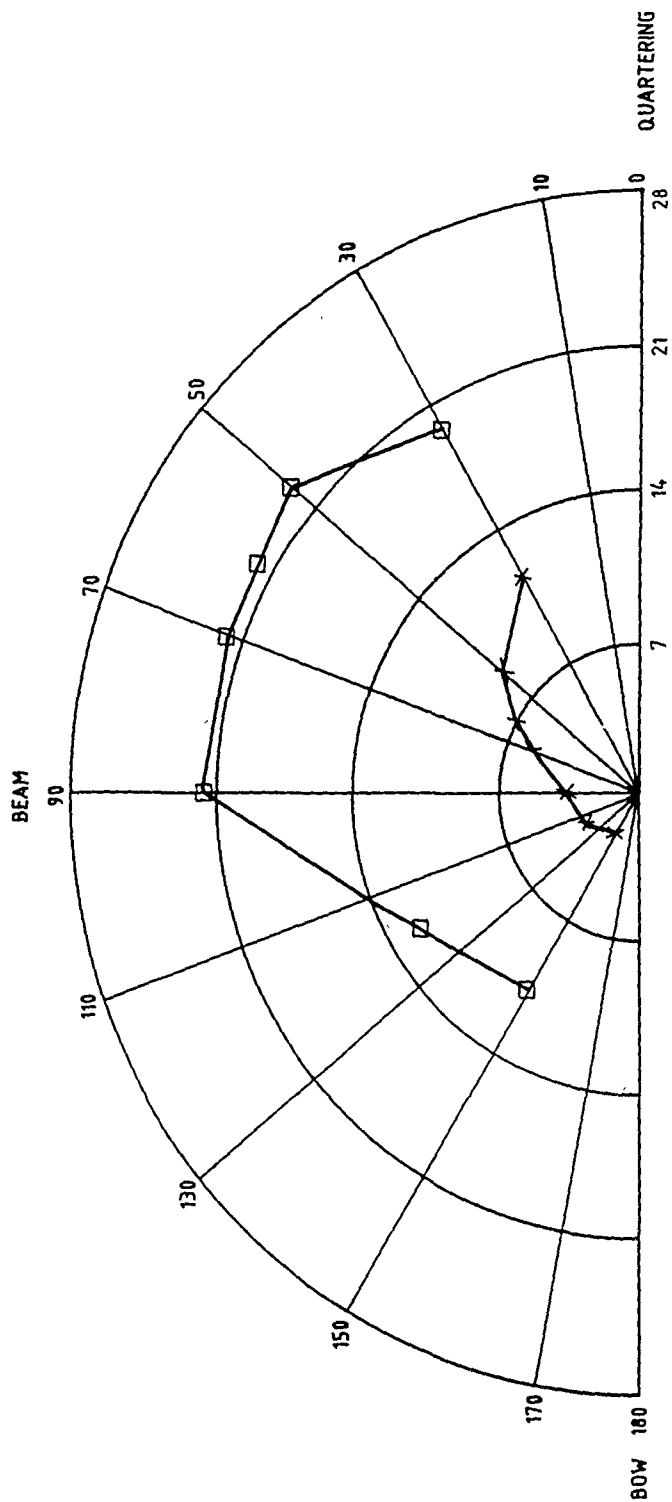


FIGURE 9 RUDDER ACTIVITY (30 KNOTS)

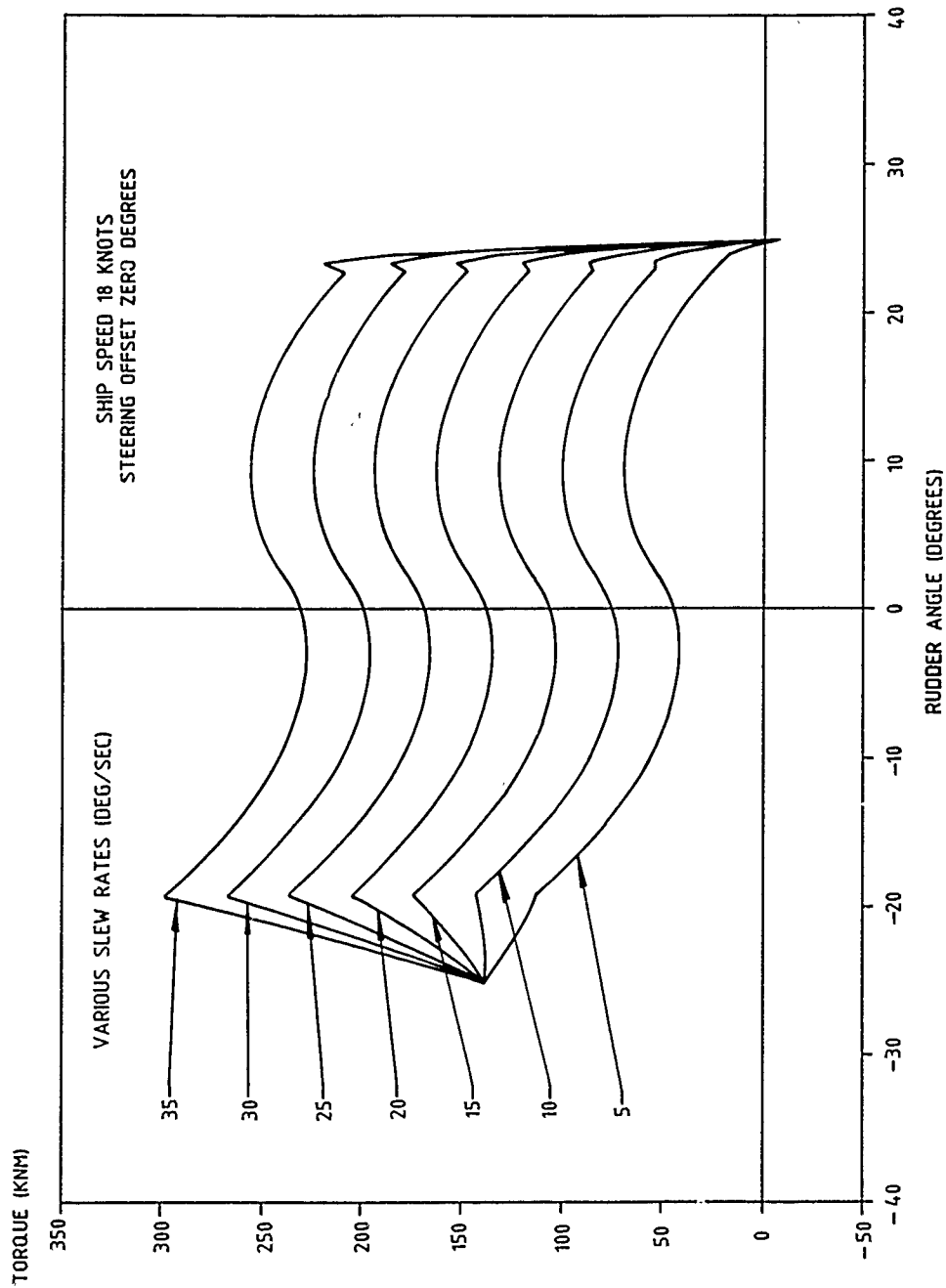


FIGURE 10 RRS STABILISING TORQUES

## ASSA: THE RRS AUTOPILOT FOR THE DUTCH M-CLASS FRIGATES

by Peter G.M. van der Klugt  
Van Rietschoten & Houwens BV Rotterdam

### 1. ABSTRACT

The last decade, Van Rietschoten & Houwens carried out a lot of research in the field of ship control systems. One of these systems, an RRS autopilot, has been developed in close cooperation with the Delft University of Technology and the Royal Netherlands Navy. This autopilot uses the rudder not only to control the heading of a ship but to reduce the roll motions simultaneously. Successful results with an early laboratory version of this autopilot were reported at the 7th SCSS in 1984. The concluding experiments with a new laboratory version comprising newly designed control algorithms were reported at the 8th SCSS in 1987. Since then, attention has been focussed on the design of an RRS autopilot for the new M-class frigates of the Royal Netherlands Navy. This paper describes the final result: the Adaptive Steering & Stabilizing Autopilot (ASSA). It summarizes the basic ideas behind ASSA, which have resulted in a rather unique layout of the system and in a new approach to user friendliness and to autopilot diagnostics.

### 2. INTRODUCTION

The last two decades have shown a remarkable change of the general opinion about Rudder Roll Stabilization. While the simple question "Is roll stabilization by means of the rudder a feasible alternative to fin stabilizers" was answer in the negative in publications such as [1], [2], [3] and [4] in the seventies, it has been Baitis [5] who paved the way for a more positive answer in the eighties.

The promising results of Baitis attracted the attention of the Royal Netherlands Navy (RNIN). The potential advantages of using the ship's rudder instead of fin stabilizers for roll stabilization such as lower costs, less drag, less noise, less space etc. encouraged them to ask the above question to the Delft University of Technology.

After having carried out extensive simulations with a ship model based on full-scale modeling trials the Delft University of Technology answered: in principle, a rudder may reduce the roll motions as good as fin stabilizers.

In fact, the results appeared to be so promising that the industry became interested [6]. In 1982 this resulted in an agreement between the Delft University of Technology, the Royal Netherlands Navy and Van Rietschoten & Houwens to design the control algorithms of a rudder roll stabilization autopilot within four years.

The first objective of the agreement was to find the answers to two pending problems:

- 1 Is it possible to realize roll stabilization by means of the rudder in practice?
- 2 Which modifications in a ship design are required to enable a successful application of a rudder roll stabilization system?

The answers were presented at the 7th SCSS in Bath (UK) in 1984[7]. A number of experiments, leading to full-scale trials on board a naval ship, demonstrated that roll stabilization by means of the rudder is indeed possible. Basing themselves on these results, the Royal Netherlands Navy decided to prefer roll stabilization by means of the rudder to roll stabilization by means of fin stabilizers in their design of the M-class frigate.

The second objective of the RRS project was to design a laboratory version of an RRS system which could be the basis for an actual realization. This objective was met in 1986 with the successful completion of experiments with a laboratory version of an RRS autopilot at the Maritime Research Institute Netherlands (MARIN) at Wageningen [8].

Since 1987 it has been up to the industry (Van Rietschoten & Houwens Rotterdam BV) to translate the results of the RRS project into a commercial product. For almost three years, their attention was being focussed in particular on the design of the Adaptive Steering & Stabilizing Autopilot (ASSA), the RRS autopilot for the M-class frigates. Several practical problems had to be solved such as

- a control panel had to be designed in cooperation with the TNO Institute of Human Perception (IZP) and the RNIN
- the design had to fit in the automation concept of the M-class frigate
- the autopilot diagnostics are substantially different from those of a common autopilot

Currently, ASSA being ready to be applied in practice, attention has switched to translating the ASSA functions into civilian derivatives. It is recognized that the ASSA technology enables the development of a number of motion-reducing systems which differ only in the motions to be reduced (roll, yaw, vertical acceleration, pitch etc.) and in the available actuators (rudder, stabilizers, air-valves etc.). The first preliminary simulations have indicated that the ASSA technology is well capable of controlling such MIMO-systems.

In this paper attention is focussed on the design of ASSA. Section 3 describes requirements for the software as well as the hardware and their consequences for the design of the control algorithms, the ship and its steering machine. Section 4 describes the principle layout of the control system and discusses the main functions of the autopilot. Finally, Section 5 summarizes the conclusions.

### 3 REQUIREMENTS

At the start of the RRS project the main target was to design within four years a prototype of an RRS autopilot which had to meet the following basic requirements:

#### 1 It should obtain the maximum roll reduction under all relevant weather conditions

- An RRS autopilot should tune itself to changing weather conditions and to changing ship dynamics (induced by load or speed changes) taking into account the system's limitations.
- Due to the limited accuracy of the sensor information and of the steering gear and due to the time lag in the control loop, it is hardly possible to reduce the roll motions of a ship if they are small and of a high frequency. However, under those circumstances roll reduction is not important. An RRS autopilot should recognize this situation and stop the roll-control action until significant roll motions occur.

#### 2 It should work safely under all weather conditions

- Due to the coupling between roll motions and yaw motions, low-frequency roll motions and high-frequency yaw motions may deteriorate the performance of an RRS system [9]. This is especially true if the control action uses the roll angle or the rate of turn as (one of the) input signal(s). An RRS autopilot should contain a filter algorithm which provides a good separation of the course control action and the roll control action (possible in the frequency domain).

- Without precautions, the limited rate of a steering machine may induce a phase lag and a low-frequency component in the control loop. These may deteriorate the performance of a ship's autopilot even to the point where the system becomes unstable [8], [9].

3 It should be user friendly as much as possible

- Controller and filter algorithms should be tuned automatically to changing weather conditions and to changing ship dynamics
- The user interface should be as simple as possible.

4 It should be able to operate satisfactorily on board any ship retrofitted with a rudder which is able to enforce roll motions

The above requirements influence the designs of the control algorithms, the user interface, the ship, its steering machine and the diagnostic system.

### Ship design and its steering machine

An RRS autopilot operates satisfactorily only if the rudder can continuously induce (preferably large) roll motions. In an early phase of the RRS project, the influence of a limited rudder angle and a limited rudder rate on the potential roll reduction was described [6]. In addition, it was demonstrated that the rudder induced roll moment is equally important [10]. Therefore, research was carried out to determine the influence of a ship design and its steering machine design on the properties of an RRS system. Subsequently, the RNIN, the Royal Schelde and Ross Industry investigated how to meet the resulting new requirements. Their work indicated that relatively minor adjustments to a ship design and its steering machine design, based on existing technology, were sufficient to meet these new requirements. The designs of the new ships of the RNIN and their steering gear were adjusted accordingly.

### Control algorithms

The LQG approach offers a convenient method to obtain the optimal control action [11]. However, before this approach may be used several conditions should be met:

- In practice, a limited number of the states of the process can be measured. An estimation filter is required to estimate the states which cannot be measured.
- The process should be linear. Therefore, precautions should be taken to prevent the steering machine from saturating.
- The parameters of the process may change (due to load changes, weather changes etc.). Therefore, an adaptation mechanism is required to estimate such parameters. Consequentially, the controller should be calculated on line.
- The quadratic criterion is a mathematical formulation of the actual criterion determined by the operator. This operator criterion is based on the rudder motions, the roll motions of the ship and its yaw motions. It changes with things such as the weather conditions and the ship's environment. Therefore, the weighting parameters of the quadratic criterion should be calculated on line by a mechanism which represents the reasoning of the human operator. This gives a second motivation to calculate the controller on line.

The safety requirement can be met by taking several precautions:

- Limitations should be added to the parameter adaptation mechanism. The adaptation has to stop at low ship speeds.
- The design of the estimation filters should be based on a robust approach using simple models of the disturbances in combination with a simple form of adaptation [9] rather than on complex models without adaptation.

- A mechanism should be added which prevents sudden large roll or yaw motions from disrupting the control action (due to the limited rudder speed) and which gains the time necessary for the adaptation mechanisms to find a new optimal controller.

### **The user interface**

Preferably, it should contain the following course-control settings:

- heading (including the direction of the turn)
- choice between "accurate" and "economic" steering
- either an adjustable rate-of-turn limitation or an adjustable rudder limitation
- alarm acknowledgement
- steering wheel

The following indications should be present:

- actual heading
- setpoint heading
- selected rate-of-turn limitation or rudder limitation
- alarm
- system stand by
- system on line (= control by autopilot)
- rudder angle(s) indication

The roll control action should add no more than one extra setting:

- roll stabilization on - roll stabilization off
- The following indications should be present:

- RRS on/off
- rudder angle(s) indication which can be used to show only the steering component of the rudder setpoint if roll stabilization is required

In the case of the M-class frigate, one important additional requirement had to be met: the RRS autopilot should fit in the automation concept of this ship. Therefore, the control panels should resemble the control panels of other control systems on board such as the propulsion control system and the diesel generator control system. This requirement has several consequences for the design of the autopilot control panel such as:

- push buttons should be used instead of switches
- a push button should become illuminated if the selection has been accepted
- a push button should flash if the selection can not be accepted
- the heading should be selected by means of a keyboard

### **The diagnostic system**

On board ships of the Royal Netherlands Navy, it is common practice to switch from autopilot to manual control (by helmsman) as soon as the autopilot indicates a breakdown of one of the components.

In the case of an RRS autopilot this is not always the proper course of action. For instance, assume that there is no wind and that the roll information gets lost. In that case, all relevant functions of the autopilot remain available as long as the weather does not change in such a way that roll stabilization becomes necessary. Thus, the availability of the course control function will be lower than that of the common autopilot. Likewise, the availability of the roll control function will be lower than that of a conventional solution such as fin stabilizers. Naturally, this situation is not desired.

To increase the availability of both the course control function and the roll control function, the operator should have answers to the following questions as soon as a system's component fails:

- Should the operator switch from autopilot to manual control or are the autopilot functions required still operational?
- Which functions are affected and to what degree?

The operator lacks the knowledge to answer these questions himself. Nor is it very practical to provide him with this knowledge because it is unlikely that he will often need such knowledge (which he therefore will easily forget) and because he has to know so many things about the other systems under his care.

An extensive diagnostic station added to the autopilot control panel with detailed information about the system's condition conflicts with the requirement of user friendliness. Nevertheless, as soon as a system's component fails an operator should be informed immediately whether manual control is required or whether the system may remain operational.

#### 4. REALIZATION

##### 4.1 Principle diagram

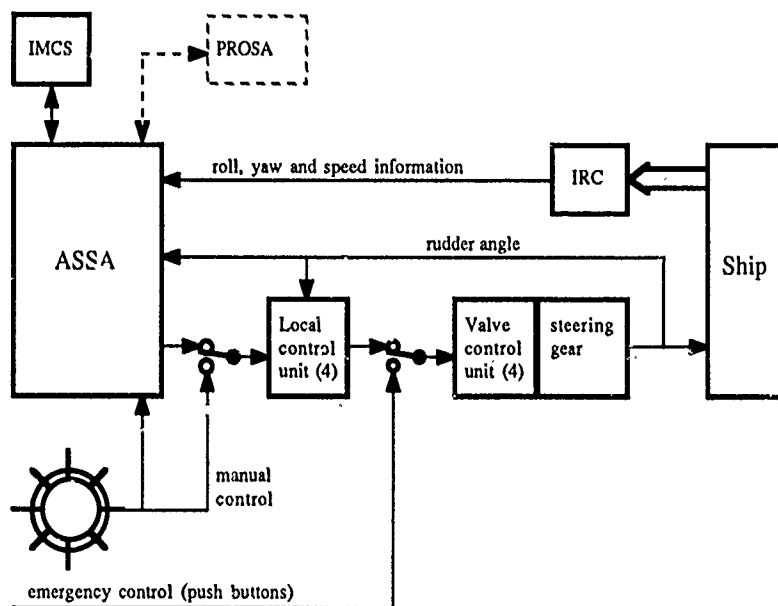


Figure 1 Principle diagram

Fig. 1 is the principle diagram of the steering system of the Dutch M-class frigates. The ship has two rudders, which can be driven by either the primary hydraulic system or a back-up system. Each hydraulic system comprises a valve control unit and a (digital) local control unit. The autopilot can be operated from two control positions.

To emphasize the basic ideas, the back-up systems and the necessary connections to make the system a fail-safe design are not shown in Fig. 1.

At the bridge, three levels of control are possible:

- Pressing the *emergency-control* push buttons overrules the other control modes by direct control of the steering gear valves.
- The local control unit controls the steering gear valves so that the rudder follows the rudder setpoint generated by the helmsman during the *manual control* mode.
- The local control unit controls the steering gear valves so that the rudder follows the rudder setpoint generated by the autopilot during the *automatic control* mode. The operator can choose between manual and automatic course keeping/changing and between roll stabilization, no roll stabilization and forced roll.

The main advantage of this approach is that the optimal control performance can be obtained under all conditions without giving in safety requirements. In the automatic control mode, the autopilot prevents that

- the roll control function deteriorates the course keeping performance if the operator requires optimal course control,
- the (adaptive) course controller becomes too weak if roll stabilization is required or
- the helmsman interferes with the roll stabilization function.

At the hydraulic systems of both rudders two lower levels of control are possible:

- manual control of the proportional valves
- a hand pump

The RRS system of the M-class frigates is designed to be a part of the automation concept of these ships. This has influenced not only the layout of the control panels but also the hardware applied:

- ASSA as well as all local control units are (standard) digital systems.
- The information retransmission system (IRC) gathers sensor information and transmits this information over serial lines to ship systems like ASSA.
- The integrated monitoring and control system (IMCS) displays diagnostic information about ship systems like the RRS system.

In Fig. 1 the module **PROSA** stands for **PR**ogram for **O**n-line **S**ignal **A**cquisition. This program runs on a portable personal computer and may be regarded as a combination of a powerful debugging device and a user-friendly data-acquisition and processing device. It is developed by van Rietschoten & Houwens for testing and monitoring of real-time digital control systems and it has proven its usefulness in several projects carried out by Van Rietschoten & Houwens. It offers extensive facilities such as:

- online data monitoring (graphical and numerical)
- modification of all variables and parameters in the target system
- program debugging stops
- event trace options
- to carry out predetermined experiments automatically
- to record a selection of the variables of the control system during measurements and to manipulate this information off-line, for instance to prove that certain requirements are met.

Currently, most monitoring & control systems designed by Van Rietschoten & Houwens contain an interface to PROSA.

#### 4.2 Control Panels

ASSA comprises two control panels:

- the bridge control panel
- the local control panel

Fig. 3 gives an impression of the layout of the local control panel. It should be noted that this figure shows a strongly simplified version of the original drawing.



The design of the control panel is based on the requirements mentioned in Chapter 3. It comprises the following functions:

- Selection/indication of the control mode
- Selection/indication of the control position
- Alarm/status indication
- Keyboard for course changes, displays (heading, setpoint heading, keyboard input), one degree port/starboard push buttons and port/starboard execute push buttons. Changing the course setpoint has to be carried out as follows
  - a Select direction (press E port side or E starboard side)
  - b Type the course desired
  - c Select execute direction (only the same push button as under "a" is allowed)
- Maximum rate of turn
- Selection/indication of the course control mode (Economic, Normal, Accurate, Optimal)
- Selection/indication of the roll stabilization mode (no stabilization, Low, Normal, Optimal, Forced Roll)
- Two displays showing either the actual angle of both rudders or the setpoint rudder used to maintain the heading of the ship (selection/indication in the middle of both displays), four emergency push buttons (non-follow-up, NFU) and information concerning the four hydraulic systems.

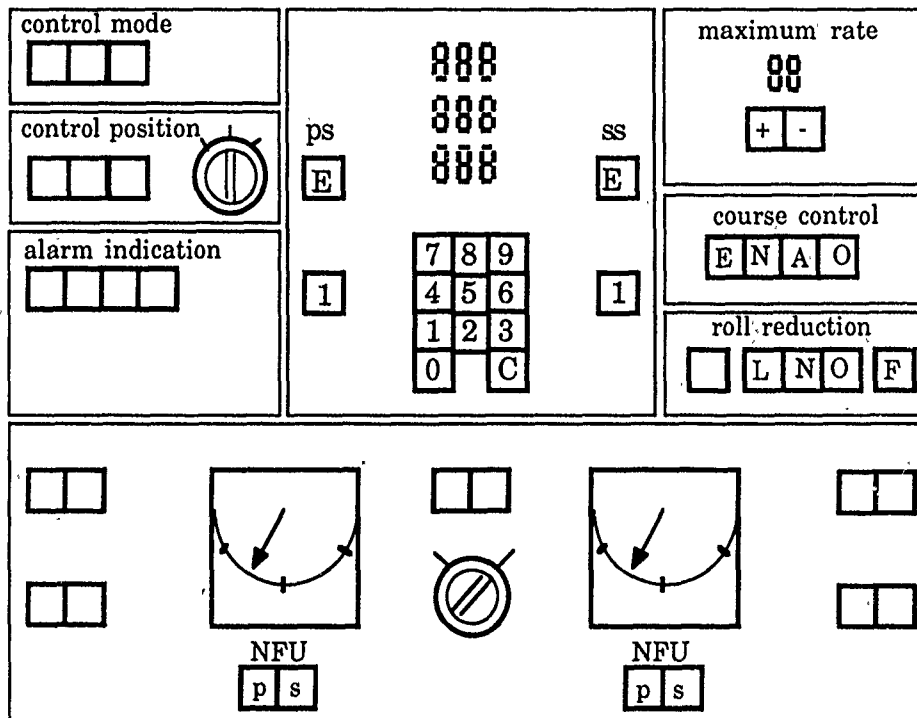


Figure 2 Layout of the Local Control Panel

In addition, the local control panel comprises a mimic panel which shows the status of the main components of the system (shown in Fig. 1).

The bridge control panel resembles very much the local control panel:

- It has a bridge-position accept push button where the operator at the local control panel may choose the control position
- It has a forced roll indication, not a forced-roll selection
- It has two indications for manual control and emergency steering while the local control panel has only one indication
- The indications meet the bridge requirements (red light instead of white)

#### 4.3 Controller design

Fig. 3 is a block diagram of the controller design.

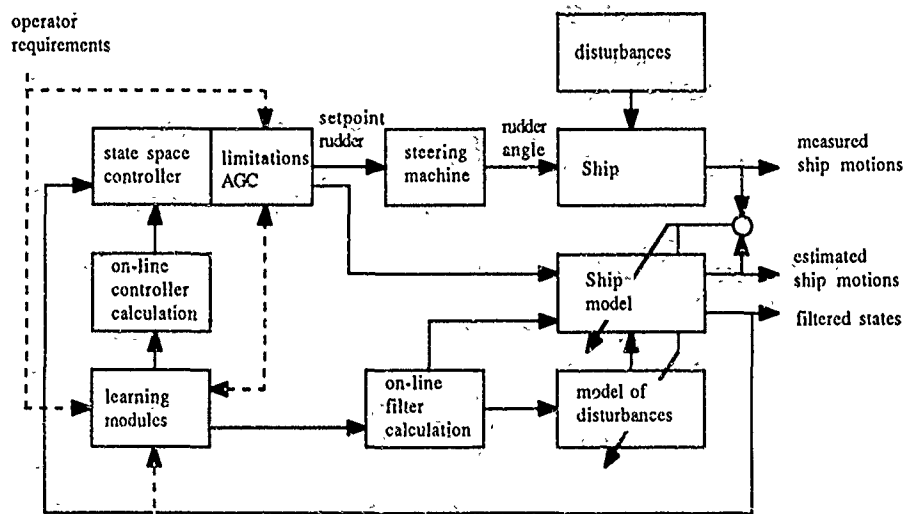


Figure 3. Principle blok diagram

The controller design comprises the following functions:

- The state estimator is based on the Kalman filter approach. It uses simplified models of the ship and its disturbances. The parameters of these models may be subject to change. The module "on-line filter calculation" adjusts the filter gains to changing model parameters and changing weather conditions.
- The optimal control action is calculated by a state space controller (LQG approach).
- The parameters of the process as well as the weighing parameters of the quadratic criterion may be subject to change. If necessary, the module "on-line controller calculation" adjusts the controller gains.
- Learning modules are present which
  - assess the weather conditions,
  - determine the weighing parameters of the quadratic criterion and
  - calculate some parameters of the process models.
- The module "limitations & AGC" takes into account the limitations of the steering gear. As indicated in [12], the limited rudder speed may induce a considerable phase lag as well as low-frequency components in the control signal.

The Automatic Gain Controller replaces this phase lag and the low-frequency components by a reduced control action [13]. Thus it guarantees the control action to remain stable under all conditions.

#### 4.4 Diagnostics

The diagnostic problem of ASSA was solved by applying human engineering as well as AI techniques. As mentioned above, the M-class frigates are equipped with an Integrated Monitoring and Control System (IMCS) which serves as a central diagnostic station. The RRS autopilot is one of the systems to be monitored. This makes it possible to have detailed diagnostic information available while the autopilot control panel remains user friendly.

The operator behind one of the ASSA control panels has a limited amount of diagnostic information at his disposal:

- "normal", indicating that the system is stand-by and that all components are operational
- "failure", indicating that the computer fails
- "alarm", indicating that he should switch from autopilot control to manual control because an essential function has failed
- "warning", indicating that something is wrong which, at the moment, does not interfere with the required autopilot functions (although in future it may)

If he requires more explicit information, he will have to contact the operators at the monitoring stations of the IMCS.

Normally, the IMCS display of ASSA shows the state of the control system. However, the operators have access to more detailed diagnostic information as soon as a malfunction of one of the system's components occurs.

Thus information is generated by a rule based module described by the functional block diagram of fig. 4.

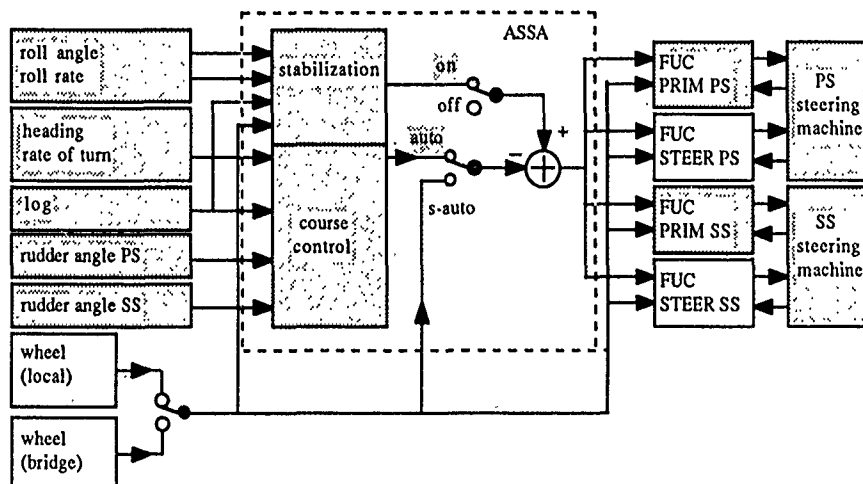


Figure 4 Functional block diagram of the RRS-autopilot

Diagnostic information is available on a component level and on a functional level:

- component failure

The components are indicated in fig. 4. The diagnostic module generates a warning as soon as a component has failed. More detailed information about the nature of the failure is available only in ASSA and not in the IMCS (in order to limit the data flow to the IMCS). Access to such information is possible by means of a special service device.

- function failure

The diagnostic module assesses the impact of a component failure on the available autopilot functions and on the required autopilot functions. It generates an alarm if one of the selected autopilot functions is seriously endangered (for instance if the heading and the rate of turn fail during automatic course keeping). It may show the consequences of a component failure on the IMCS (for instance automatic course keeping possible/deteriorated/not possible) and it gives advice about the proper course of action.

## 5. CONCLUSIONS

This paper presents the final result of eight years of research in the field of rudder roll stabilization: the Adaptive Stabilizing Ship's Autopilot (ASSA). Attention is focussed on the functional layout of the control system and the control algorithms and on the included diagnostic system. The following conclusions can be drawn:

- Application of Artificial Intelligence (AI) principles offers attractive advantages in the field of ship-motion control systems.

This paper describes the main characteristics of the RRS autopilot of the Dutch M-class frigates. This autopilot can be regarded as the first of a new generation of ship's autopilots which combines modern control algorithms with the advantages of applying AI principles.

Not only is such an autopilot better suited to deal with rapidly changing weather conditions at sea, but it is able to deal with the (often conflicting) operator requirements as well. In addition, it can take into account the limitations of a ship and its steering machine when it calculates the optimal (with respect to the operator requirements) control action. Finally, the up time of the system has been improved because it may offer detailed advice to the operator, should one of the system's components fail.

- Ship-motion control systems should be based on a criterion which is adjusted to weather conditions, to the system's limitations and to the operator requirements.

In control engineering, it is common practice to design a controller based on a criterion with fixed weighting parameters. In the case of ship-motion control systems, this is not the proper course of action. This has been illustrated in [14] by summarizing the many criteria described in the literature in the field of course-keeping controllers. Different autopilot designers may use different weighting parameters to design an "optimal" controller and claim that their controller is better than others.

In practice, it is not possible to design one criterion which covers all conditions at sea. [15] advises that the operator should be able to modify the criterion by selecting between economic and accurate steering. Changing weather conditions should be taken into account by applying an adaptive filter which removes high-frequency components from the course-control loop. However, in practice this approach yields a satisfactory performance under most conditions while the controller design proposed in this paper yields a satisfactory performance under all relevant conditions.

- ASSA is ready to be applied in practice

The control algorithms have been tested by means of simulation experiments, scale model experiments and experiments on board several ships of the Royal Netherlands Navy. In 1989 a new test simulator was built which enables to test all functions of ASSA.

At the moment, the first system, connected to the test simulator, is undergoing an endurance test before the final installation on board (June 1990). The ship is planned to sail shortly after this conference. By that time, also the first civilian derivative of ASSA will have undergone endurance tests on board a mercantile ship.

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## **PATH TRACKING OF SURFACE SHIPS USING MULTIVARIABLE SLIDING MODE CONTROL**

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### **1. ABSTRACT**

The surface ship path control problem is formulated as a multivariable non-linear state space control problem subject to disturbances, modeling errors, and parameter uncertainty. A 'destroyer study' ship using a non-linear maneuvering model coupled with the ship propulsion dynamics is used as the system model. The system to be controlled is highly non-linear with parameters that vary with speed and operational conditions. Uncertainty in the force and propulsion coefficients, as well as in the disturbances of the seaway lead to the need for a robust control for navigational accuracy.

In recent times, the development of Variable Structure Control in the form of Sliding Modes has been shown to provide added robustness that is quite remarkable for autopilot systems. This paper develops a technique for designing multivariable sliding mode controllers for autopilots with combined steering and speed control for surface ships, and presents results based on computer simulations using the model described above. The results illustrate the simplicity and effectiveness of the robust control design for compensating the non-linearities and disturbance effects with improvements in the navigational accuracy.

### **2. INTRODUCTION AND EQUATIONS OF MOTION**

The problem of controlling surface ships along prescribed paths is becoming increasingly important from operational, cost, safety, and environmental viewpoints. Autopilots are commonly used for steady state course keeping and course changing in open and restricted waters. In these situations, ships are subject to essentially

constant, non-zero mean disturbances such as those due to current, wind and bank proximity effects. Ships are also subject to zero mean, random or slowly varying, disturbances such as those due to waves and passing ships. Furthermore, the dynamics of a ship change significantly with loading conditions, water depth, and speed; thus introducing another degree of uncertainty between the actual ship and its mathematical model. While questions pertaining to fluid-body interaction and reliable prediction of hydrodynamic forces are still the subject of current research, design and installation of ship automatic controllers is a matter of immediate need.

Any automatic controller design for a ship must satisfy two conflicting requirements: first, it has to be sophisticated enough to perform its mission in the realm of complicated and ever-changing ship/environment interactions; and second, it has to be simple enough so that on-line implementation is possible by the onboard ship computer at a sufficiently high sample rate. The first autopilots in use were based on PID-control as proposed by Minorsky [1]. Although simplified maneuvering models based on Nomoto's first-order model have been proposed for ship control [2], it has been realized that nonlinear effects and uncertainties must be taken into account in the autopilot design [3]. Current design procedures include conventional state space steering systems [4], LQG design to minimize the added resistance due to steering [5], LQG design for path keeping [6], adaptive steering [7], [8], adaptive path keeping [9], multivariable integral control for path keeping [10], and discrete-time adaptive stochastic path keeping control laws [11]. At the same time, propulsion control is achieved through use of gain scheduling techniques [12] in order to overcome the highly nonlinear nature of the propulsion system dynamics.

This paper addresses the problem of ship maneuvering while keeping a specified speed profile. The operational scenario is to be able to go through a sequence of way-points at a user-specified forward speed. The controller design must take into account the nonlinear form of the system equations, and must be robust enough in order to be able to carry its mission given a limited set of measurements and in the presence of environmental changes and actual/mathematical model mismatch. As an alternative to the aforementioned techniques we investigate here the use of a Variable Structure (also called Sliding Mode) controller for the ship path tracking problem. Sliding mode controllers [13], [14] have very good robustness characteristics and they constitute a very attractive design alternative in cases where significant uncertainties exist in the modeling of the physical plant.

The mathematical model consists of the nonlinear surge, sway, and yaw equations as described in [15]. In a moving coordinate frame fixed at the ship's geometrical center, Newton's equations of motion are

$$m(\dot{u} - rv) = X, \quad (1)$$

$$m(\dot{v} + ru) = Y, \quad (2)$$

$$I_z \dot{r} = N, \quad (3)$$

where  $u$ ,  $v$ ,  $r$  are the surge, sway, yaw velocities of the ship, and  $X$ ,  $Y$ ,  $N$  represent the total excitation forces and moment, respectively. Following standard ship maneuvering assumptions, these forces are represented by memoryless polynomials of up to third order in  $u$ ,  $v$ ,  $r$ . In this way the equations of motion in the horizontal plane become

$$(m - \frac{1}{2}\rho\ell^3 X'_u)\dot{u} = T(1 - t) - R + \frac{1}{4}\rho\ell^2 X'_{uv}v^2 + (\frac{1}{2}\rho\ell^3 X'_{ur} + m)vr + \frac{1}{4}\rho\ell^2 X'_{\delta\delta}u^2\delta^2, \quad (4)$$

$$(m - \frac{1}{2}\rho\ell^3 Y'_v)\dot{v} = \frac{1}{2}\rho\ell^2 Y'_{uv}uv + \frac{1}{12}\rho\ell^2 Y'_{vvv}\frac{v^3}{u} + \frac{1}{4}\rho\ell^4 Y'_{vrr}\frac{vr^2}{u} + (\frac{1}{2}\rho\ell^3 Y'_r - m)ur + \frac{1}{4}\rho\ell^3 Y'_{rvv}\frac{rv^2}{u} + \frac{1}{2}\rho\ell^2 Y'_\delta u^2\delta + \frac{1}{12}\rho\ell^2 Y'_{\delta\delta\delta}u^2\delta^3, \quad (5)$$

$$(I_z - \frac{1}{2}\rho\ell^5 N'_r)\dot{r} = \frac{1}{2}\rho\ell^3 N'_{uv}uv + \frac{1}{12}\rho\ell^3 N'_{vvv}\frac{v^3}{u} + \frac{1}{4}\rho\ell^5 N'_{vrr}\frac{vr^2}{u} + (\frac{1}{2}\rho\ell^4 N'_r - mx_G)ur + \frac{1}{4}\rho\ell^4 N'_{rvv}\frac{rv^2}{u} + \frac{1}{2}\rho\ell^3 N'_\delta u^2\delta + \frac{1}{12}\rho\ell^3 N'_{\delta\delta\delta}u^2\delta^3, \quad (6)$$

where only the coefficients that have nonzero values in the present model have been kept. Since the primed variables represent the nondimensional hydrodynamic coefficients, the above equations are dimensional. We have chosen to work with the dimensional form of the equations because one of the goals of this work is to establish system performance under a wide variation of forward speeds. Note from the form of equations (4), (5), and (6) that the nonlinear terms become very important for low speed maneuvering whereas at high speeds  $u$  (and consequently relatively low angle of attack with respect to the water), the steering response is predominantly linear. It follows that the model describing the system dynamics is a function of time or, which amounts to the same thing, a function of the maneuver at hand. If the autopilot is to cater for speed changes and the execution of large maneuvers without any time consuming adaptation or gain scheduling, then it needs to have a very robust response. This fact led to the adoption of a sliding mode design as developed in Section 3.

The ship resistance  $R$  (in Nt) is given as a function of speed  $u$  (in m/s) by

$$R = 3623.2u + 5.57u^3, \quad (7)$$

and the thrust deduction factor by

$$1 - t = 0.914 - 0.00072u + 0.0000106u^2. \quad (8)$$



These equations were obtained by curve-fitting of the data presented in [15]. The open-water propeller thrust  $T$  is calculated from the equation

$$T = C_T \rho D^2 [u^2 (1 - W')^2 + n^2 D^2], \quad (9)$$

where  $n$  is the propeller revolutions per second,  $D$  the propeller diameter,  $W'$  the wake fraction

$$1 - W' = 0.966 - 0.00098u + 0.0000116u^2 \quad (10)$$

and the thrust coefficient  $C_T$  is given by

$$C_T = -0.4 + 0.71\epsilon, \quad u(1 - W') > 0, \quad n > 0, \quad (11)$$

where

$$\epsilon = \frac{nD}{[u^2(1 - W')^2 + n^2 D^2]^{1/2}}. \quad (12)$$

The propeller revolutions  $n$  can be coupled to the power plant dynamics as in [15]. However, since that model is valid for slow increases in the fuel flow rate, it cannot predict accurately rapid maneuvering, and is therefore not included here. Although it is recognized that the steering gear is both rate and angle limited [16], steering gear dynamics are not included in the formulation since, usually, they are much faster than the dynamics of a turning ship. The methods presented in the following sections can easily accommodate such modifications if desired.

To complete the model we need the expressions for the ship Euler angle rate (yaw)

$$\dot{\psi} = r, \quad (13)$$

and the inertial position rates

$$\dot{x} = u_{co} + u \cos \psi - v \sin \psi, \quad (14)$$

$$\dot{y} = v_{co} + u \sin \psi + v \cos \psi, \quad (15)$$

where  $u_{co}$  and  $v_{co}$  are the current velocities. The heading measurement dynamics can be modeled by a set of nonlinear differential equations [17], which describe the effects on the gyrocompass of the ship roll and pitch motions. These effects result in an oscillatory random perturbation (disturbance) and a constant bias. The former is compensated by the sliding mode autopilot whereas the latter, which would result in a steady state course error, is corrected by the navigational system of the ship.

### 3. CONTROL DESIGN

The equations describing the system dynamics, (4) through (13) of Section 2, can be written as a set of 4 nonlinear coupled differential equations in the form

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}) + \mathbf{g}(\mathbf{x}, \mathbf{u}) , \quad (16)$$

where the state vector is

$$\mathbf{x} = [u, \psi, v, r]^T , \quad (17)$$

and the control vector is

$$\mathbf{u} = [n, \delta]^T . \quad (18)$$

It should be noted that any finite dimensional control system can be written without loss of generality as in (16). We wish to design a (possibly nonlinear) control law to guarantee global asymptotic stability of system (16). If  $\mathbf{x} \in R^n$  and  $\mathbf{u} \in R^m$  with  $m \leq n$  we define the linear hyperplane

$$\begin{aligned} \Sigma(\mathbf{x}) &= \mathbf{S}^T \mathbf{x} = 0 \quad , \quad \mathbf{S} \in R^{n \times m} , \text{ or} \\ \Sigma(\mathbf{x}) &= [\sigma_1, \sigma_2, \dots, \sigma_m]^T = [\mathbf{s}_1^T \mathbf{x}, \mathbf{s}_2^T \mathbf{x}, \dots, \mathbf{s}_m^T \mathbf{x}] , \end{aligned}$$

and the Lyapunov function

$$V(\mathbf{x}) = \frac{1}{2}(\Sigma^T \Sigma) = \frac{1}{2}(\sigma_1^2 + \sigma_2^2 + \dots + \sigma_m^2) .$$

Global asymptotic stability of  $\Sigma(\mathbf{x})$  is guaranteed if

$$\dot{V}(\mathbf{x}) < 0 \quad \text{or} \quad \sigma_1 \dot{\sigma}_1 + \sigma_2 \dot{\sigma}_2 + \dots + \sigma_m \dot{\sigma}_m < 0 ,$$

which can (rather conservatively) be achieved if

$$\sigma_i \dot{\sigma}_i < 0 \quad \text{or} \quad \dot{\sigma}_i = -\eta_i^2 \text{sign}(\sigma_i) \quad , \quad i = 1, 2, \dots, m ,$$

or, using (16),

$$\mathbf{s}_i^T (\mathbf{f}(\mathbf{x}) + \mathbf{g}(\mathbf{x}, \mathbf{u})) = -\eta_i^2 \text{sign}(\sigma_i) .$$

In matrix form, this equation is written as

$$\mathbf{S}^T (\mathbf{f}(\mathbf{x}) + \mathbf{g}(\mathbf{x}, \mathbf{u})) = -\mathbf{k}_n , \quad (19)$$

where the  $R^m$  vector  $\mathbf{k}_n$  is defined by

$$\mathbf{k}_n = [\eta_1^2 \text{sign}(\sigma_1), \dots, \eta_m^2 \text{sign}(\sigma_m)]^T .$$

Further development is significantly simplified if system (16) is linear in the control effort, i.e.,

$$\dot{x} = f(x) + g(x)u . \quad (20)$$

Then, equation (19) can be solved directly for  $u$

$$u = - (S^T g(x))^{-1} S^T f(x) - (S^T g(x))^{-1} k_n , \text{ or} \quad (21)$$

$$u = \hat{u} + \bar{u} .$$

This feedback control law is composed of two parts. The first,

$$\hat{u} = - (S^T g(x))^{-1} S^T f(x) \quad (22)$$

is a nonlinear feedback law based on model (20), whereas the second

$$\bar{u} = - (S^T g(x))^{-1} k_n \quad (23)$$

is a nonlinear feedback which has components with signs toggling between plus and minus according to the sign functions  $\text{sign}(\sigma_i)$ . It is  $\bar{u}$  which is mainly responsible for driving and keeping the system onto the sliding plane  $\Sigma(x) = 0$  (where  $\bar{u} = 0$  as well). Provided the gains  $\eta_i^2$  have been chosen large enough,  $\bar{u}$  can provide the desired robustness due to momentary disturbances and unmodeled dynamics without any compromise in stability.

It should be mentioned that, more generally, system (20) can be written as

$$\dot{x} = f(x) + g(x)u + \delta f , \quad (24)$$

where  $\delta f$  represents external disturbances, errors arising from incomplete knowledge of  $f(x)$ , and higher-order terms in the Taylor expansion of  $g(x, u)$  in terms of  $u$ . In such a case, the switching gains  $\eta_i^2$  must be selected so that

$$\eta_i^2 > \|s_i^T\| \cdot \|\delta \hat{f}_i\| ,$$

where  $\delta \hat{f}$  is an estimate of  $\delta f$ .

The unknown coefficients of  $S$  in (21) are specified such that system (20) has the desired dynamics on the sliding plane  $\Sigma(x)$ . Linearizing (20) around a nominal operation condition we get

$$\dot{x} = Ax + Bu , \quad A \in R^{n \times n} , \quad B \in R^{n \times m} \quad (25)$$

Using the QR-factorization of  $B$  we can find an orthogonal transformation matrix  $T$  such that

$$TB = \begin{bmatrix} B_1 \\ 0 \end{bmatrix} , \quad B_1 \in R^{m \times m} .$$

Then using the transformation  $y = Tx$ , system (25) becomes

$$\dot{y}_1 = A_{11}y_1 + A_{12}y_2 + B_1u, \quad (26)$$

$$\dot{y}_2 = A_{21}y_1 + A_{22}y_2, \quad (27)$$

where  $y_1 \in R^{m \times 1}$ ,  $y_2 \in R^{(n-m) \times 1}$ ,  $A_{11} \in R^{m \times m}$ ,  $A_{12} \in R^{m \times (n-m)}$ ,  $A_{21} \in R^{(n-m) \times m}$ ,  $A_{22} \in R^{(n-m) \times (n-m)}$ ,  $B_1 \in R^{m \times m}$ , and  $u \in R^{m \times 1}$ . The sliding plane  $S^T x = 0$  becomes  $C^T y = 0$  with  $C = TS$ , or  $C_1^T y_1 + C_2^T y_2 = 0$  and, without loss of generality, we can choose  $C_1 = I$ . Therefore, the equation for the sliding plane becomes

$$y_1 + C_2^T y_2 = 0. \quad (28)$$

Since  $\bar{u} = 0$ , the control  $u = \hat{u}$  which, based on the linearized transformed system (25) is

$$\hat{u} = -B_1^{-1} [(A_{11} + C_2^T A_{21})y_1 + (A_{12} + C_2^T A_{22})y_2]. \quad (29)$$

Using (28) and (29), the first set of equations on the sliding plane, (26), becomes

$$-C_2^T \dot{y}_2 = -C_2^T (A_{21}y_1 + A_{22}y_2),$$

which is a linear combination of the second set (27). Therefore, the dynamics on the sliding plane are governed by the reduced  $(n - m)$ th order system

$$\dot{y}_2 = A_{22}y_2 + A_{21}y_1, \quad y_1 = -C_2^T y_2. \quad (30)$$

The gain vector  $C_2$  can be found by using standard linear system techniques such as poleplacement or LQR, and then  $S = T^T C$ . Therefore, the nonlinear control law (21) is completely determined.

It should be mentioned that, since on the sliding plane the first  $m$  equations (26) are a linear combination of the other  $n - m$  equations (27), the closed loop dynamics matrix of (25) has  $m$  poles located at the origin. This is consistent with our decomposition  $u = \hat{u} + \bar{u}$ . The  $\hat{u}$  part provides the desired dynamics on the sliding plane. Therefore,  $\hat{u}$  has no effect in the  $m$ -dimensional subspace orthogonal to  $S^T x = 0$ .

In the following, the control law (21) will be referred to as "nonlinear", whereas by an abuse of terminology, a control law of the form

$$u = -(S^T B)^{-1} S^T A x - (S^T B)^{-1} k_n, \quad (31)$$

based on the linearized system (25) will be referred to as "linear" in spite of the nonlinear swithing term  $k_n$ . The term  $(S^T B)$  is nonzero as a direct consequence of the controllability of the system.

#### 4. AUTOPILOT DYNAMICS

In the present application, upon linearization of the nonlinear equations of motion (4) to (13), two separate non-interacting linear subsystems emerge: one for the surge velocity  $u$  (the propulsion subsystem); and one for the yaw angle  $\psi$ , sway velocity  $v$ , and yaw rate  $r$  (the steering subsystem). The steering subsystem is

$$\dot{\psi} = r, \quad (32)$$

$$(m - \frac{1}{2}\rho\ell^3 Y_v')\dot{v} = \frac{1}{2}\rho\ell^2 Y_v' u_0 v + (\frac{1}{2}\rho\ell^3 Y_r' - m)u_0 r + \frac{1}{2}\rho\ell^2 Y_\delta' u_0^2 \delta, \quad (33)$$

$$(I_z - \frac{1}{2}\rho\ell^5 N_r')\dot{r} = \frac{1}{2}\rho\ell^3 N_v' u_0 v + (\frac{1}{2}\rho\ell^4 N_r' - m x_G)u_0 r + \frac{1}{2}\rho\ell^3 N_\delta' u_0^2 \delta, \quad (34)$$

where  $u_0$  is the nominal forward speed, and the propulsion subsystem is

$$(m - \frac{1}{2}\rho\ell^3 X_u')\dot{u} = \frac{\partial[T(1-t) - R]}{\partial u}(u - u_0) + \frac{\partial T}{\partial n}(n - n_0), \quad (35)$$

where the propeller revolutions  $n_0$  can be found from

$$T(u_0, n_0)(1 - t(u_0)) = R(u_0). \quad (36)$$

The sliding plane coefficients can then be designed independently using the above two single input systems. For the steering subsystem we have

$$\sigma_1 = s_1 \psi + s_2 v + s_3 r, \quad (37)$$

whereas for the propulsion subsystem

$$\sigma_2 = s_4(u - u_0). \quad (38)$$

Then the steering control law becomes

$$\delta = -\alpha(s_1 r + s_2 f_2 + s_3 f_3) - \alpha\eta_1^2 \text{sat} \text{sgn}(\sigma_1), \quad (39)$$

where

$$\alpha = \left( s_2 \frac{0.5\rho\ell^2 Y_\delta' u_0^2}{m - 0.5\rho\ell^3 Y_v'} + s_3 \frac{0.5\rho\ell^3 N_\delta' u_0^2}{I_z - 0.5\rho\ell^5 N_r'} \right)^{-1}, \quad (40)$$

$$f_1 = r, \quad (41)$$

$$f_2 = \left( \frac{1}{2}\rho\ell^2 Y_v' uv + \frac{1}{2}\rho\ell^2 Y_{vvv}' \frac{v^3}{u} + \frac{1}{4}\rho\ell^4 Y_{vrr}' \frac{vr^2}{u} + (\frac{1}{2}\rho\ell^3 Y_r' - m)ur + \frac{1}{4}\rho\ell^3 Y_{rvv}' \frac{rv^2}{u} \right) (m - \frac{1}{2}\rho\ell^3 Y_v')^{-1}, \quad (42)$$

$$f_3 = \left( \frac{1}{2} \rho \ell^3 N'_{uv} uv + \frac{1}{12} \rho \ell^3 N'_{vvv} \frac{v^3}{u} + \frac{1}{4} \rho \ell^5 N'_{vrr} \frac{vr^2}{u} + \left( \frac{1}{2} \rho \ell^4 N'_r - mx_G \right) ur + \frac{1}{4} \rho \ell^4 N'_{rvv} \frac{rv^2}{u} \right) (I_z - \frac{1}{2} \rho \ell^5 N'_r)^{-1}, \quad (43)$$

and the propulsion control law

$$n = n_0 - \eta_2^2 \text{satsgn}(\sigma_2), \quad (44)$$

with  $\sigma_1$  and  $\sigma_2$  given by (37) and (38), respectively.

Results for the propulsion subsystem are presented in the following section. The steering control law was designed for a nominal forward speed of Froude number  $F_n = 0.2$  and closed loop poles on the sliding plane were selected at  $-0.5$  and  $-0.51$ . The nonlinear gain is  $k_n = 2$  and we use

$$\text{satsgn}(\sigma) = \begin{cases} +1 & \text{if } \sigma > \phi \\ -1 & \text{if } \sigma < -\phi \\ \sigma/\phi & \text{if } -\phi \leq \sigma \leq \phi \end{cases}$$

instead of the pure switch  $\text{sign}(\sigma)$  in order to avoid control chattering. For the simulations presented here, the above "boundary layer thickness"  $\phi$  was fixed at 0.1. It should be mentioned that in real life applications, the choice of  $\phi$  is not very crucial since the presence of lags between commanded and actual rudder angle helps to reduce chattering even further.

Figure 1 shows a comparison based on simulations of the linear and the nonlinear steering equations of motion. The rudder angle  $\delta$  is limited to  $\pm 0.4$  radians. A linear, as in (31), steering control law was used, and it can be seen that the performance is excellent even in the case of the nonlinear simulation, despite the presence of all the nonlinear terms in the equations of motion.

This remarkable robustness of the design is illustrated in Figure 2, where the same linear control law based on the nominal  $F_n = 0.2$  is tested against the nonlinear vehicle under a wide variation in the forward speed. Although, so far, perfect and complete state measurements have been assumed, it can be shown [18] that the design retains its robustness properties with state observers. A linear reduced order observer can be designed here for the sway velocity  $v$  assuming measurements of  $\psi$  and  $\dot{\psi}$ . However, we have observed that for surface ship and submarine maneuvering, a sway velocity observer provides little or no improvement over no feedback of  $v$  at all, i.e., assuming  $\hat{v} = 0$ . In the following, all simulations are performed using the nonlinear control law as in (21) based on the full nonlinear equations of motion, and using the assumption that  $\hat{v} = 0$ .

In Figure 3, the performance of such a control law is shown under a 10:1 variation in the forward speed. Again, the control is excellent in spite of the model/controller

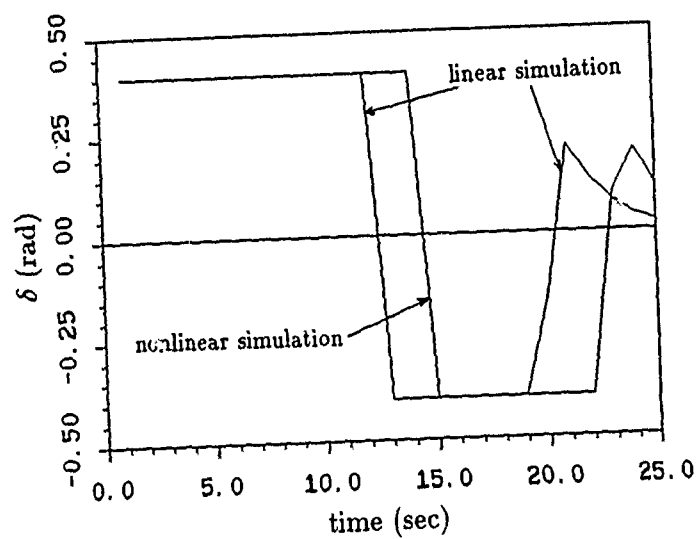
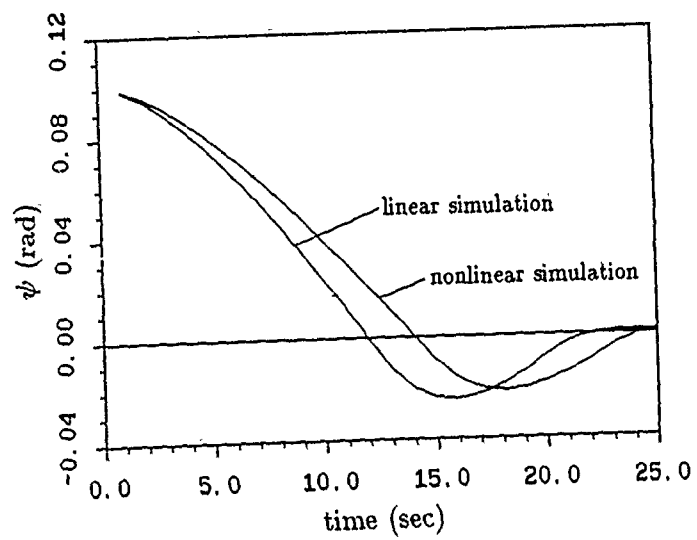


Fig. 1. Linear steering control: Linear vs. nonlinear simulation.

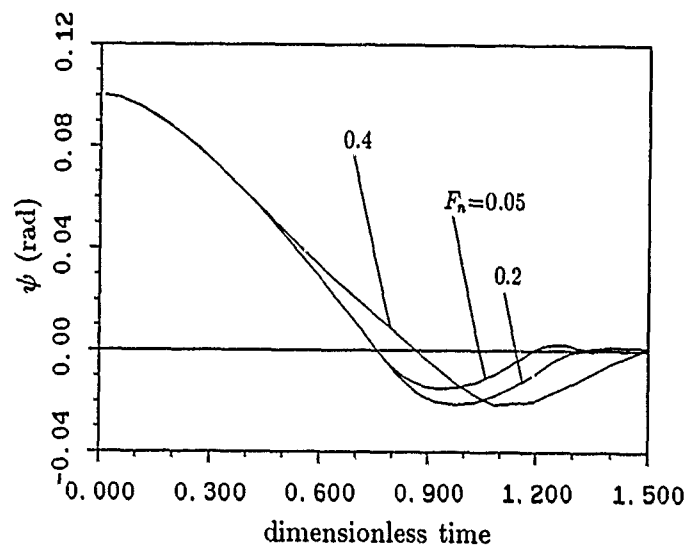
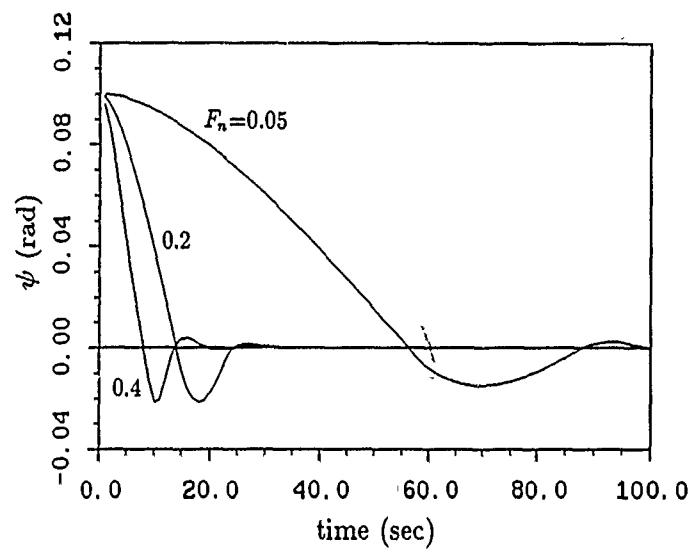


Fig. 2. Linear steering control: Froude number effect.



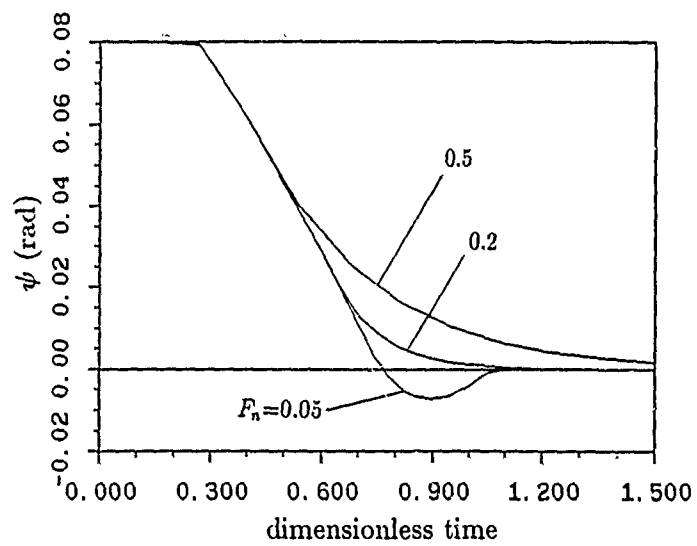
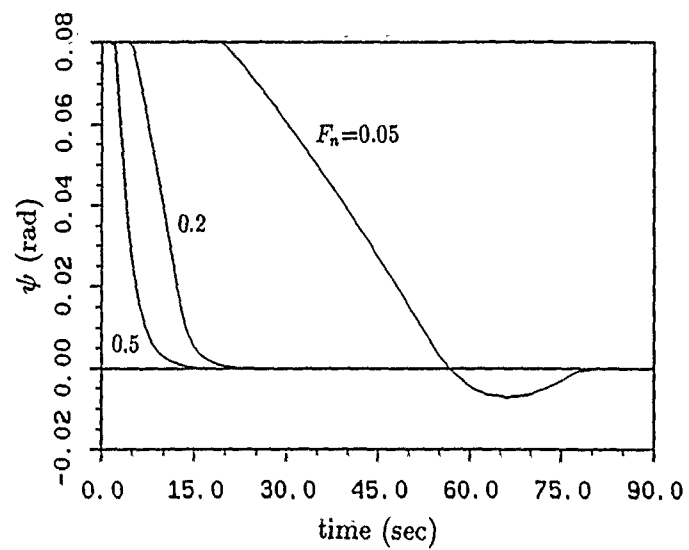


Fig. 3. Nonlinear steering control: Froude number effect.

mismatch arising from  $\hat{v} = 0$  and the differences in speed. It is worth noting that upon nondimensionalizing time by the forward speed and ship length, the three curves of Figures 2 and 3 appear to be much closer to each other. The remaining differences can be attributed to the existence of the nonlinear terms in the equations of motion and the assumption that  $\hat{v} = 0$ .

## 5. NAVIGATION SCHEME

Based on the discussion of the previous section, two sliding mode autopilots are designed, one for propulsion and one for steering control. These autopilots are called to provide ship path tracking in the sense of passing through a series of way-points at a specified speed. One approach could be to assume that the desired path is a straight line. This does not alter the essential characteristics of the path keeping problem and is typical in ship maneuvering situations where the ship is to follow a series of straight paths or leading line segments. Such an approach, however, would require the incorporation of the lateral deviation equation (15) — after appropriate coordinate system rotations between consecutive way-points — in the control law design. This results in an increase in the system dimensionality by one. Since the main goal of this paper is the design of a robust autopilot, such a dimensionality increase is undesirable. For this reason, we use a line-of-sight navigational scheme, where the commanded heading angle becomes a function of the current ship position and the next way-point. The way-point has then been reached when its distance from the ship (target radius) is less than some specified value. Although such a simple navigation scheme will, in general, result in a softer vehicle response; i.e., a trajectory which lags the specified straight line segments through the way-points, it offers several advantages that led to its consideration:

1. It leads to autopilot designs that give rise to stable response over a wide variation in the forward speed and ship hydrodynamic coefficients.
2. It separates the controller from the navigator design, thus making it possible to study the effects of parameter changes in the one regardless of the other.
3. Accurate path tracking can be achieved by a judicious choice of way-points taking into account the open loop transfer and advance characteristics of the ship. This can be done by a command generation algorithm external to the autopilot. Such a way-point selection can also help in reducing or eliminating steady state errors in the presence of constant disturbances without the need for integral control.

4. Inertial position information updates are less frequently needed than yaw angle or yaw rate.

Simulation results are presented based on the following operational scenario, with the ship initially at the origin:

- Go to point  $(x, y) = (5, 0)$  ship lengths with a Froude number  $F_n = 0.15$ .
- Turn to  $(x, y) = (20, 5)$  while accelerating to  $F_n = 0.25$ .
- Turn to  $(x, y) = (15, 20)$  while keeping constant speed.
- Return to the origin  $(0, 0)$  while accelerating to  $F_n = 0.40$ .

A nonlinear control law (according to the terminology adopted in Section 3) was used for the steering subsystem, assuming  $\hat{v} = 0$ . This eliminates the need for a doppler sonar or a sway velocity observer. The rest of the state variables are assumed to be measurable, including the availability of location from GPS or INS data. For speed control, a linear as in (44) control law was used. This was done because in this case, due to the nonzero set point in speed, a nonlinear control law would require a time consuming iterative solution for  $n$ . Due to the low dimensionality of the propulsion subsystem, a linear sliding mode control is very robust and should be able to account for the controller/plant mismatch.

Results for the aforementioned sequence of way-points are presented in Figure 4, where the basic features of the line-of-sight navigator are illustrated. More accurate path tracking can be achieved by providing more way-points. It is also clear that relaxing the target radius requirement (a value of 0.1 ship lengths was used in the simulations) will result in an "anticipation" of the turn and less deviation from an assumed straight line path. The propulsion control responds very rapidly to speed commands despite the added drag during the turn. The saturation limit for the shaft revolutions was set at 114 rpm, which corresponds to a steady state speed of  $F_n = 0.50$ .

The same sequence of way-points is used in Figure 5, this time with a constant lateral current in the  $y$ -direction of  $v_{co} = \pm 2\text{m/sec}$  (4 knots). The controller was able to drive the ship through the way-points in spite of the constant disturbance and the lack of integral control, or current estimation and feedforward. If more detailed path keeping is desired, it can be easily provided by a local path planner or command generation system generating more way-points located closer to each other.

The robustness of the stability properties of the design is illustrated in Figure 6. Together with the nominal ship response, two more cases are shown:

- Case 1: Same (nominal) control law with the  $Y_v$ ,  $N_r$  hydrodynamic coefficients used in the simulation reduced to  $0.1Y_v$  and  $0.1N_r$ , and rudder coefficients

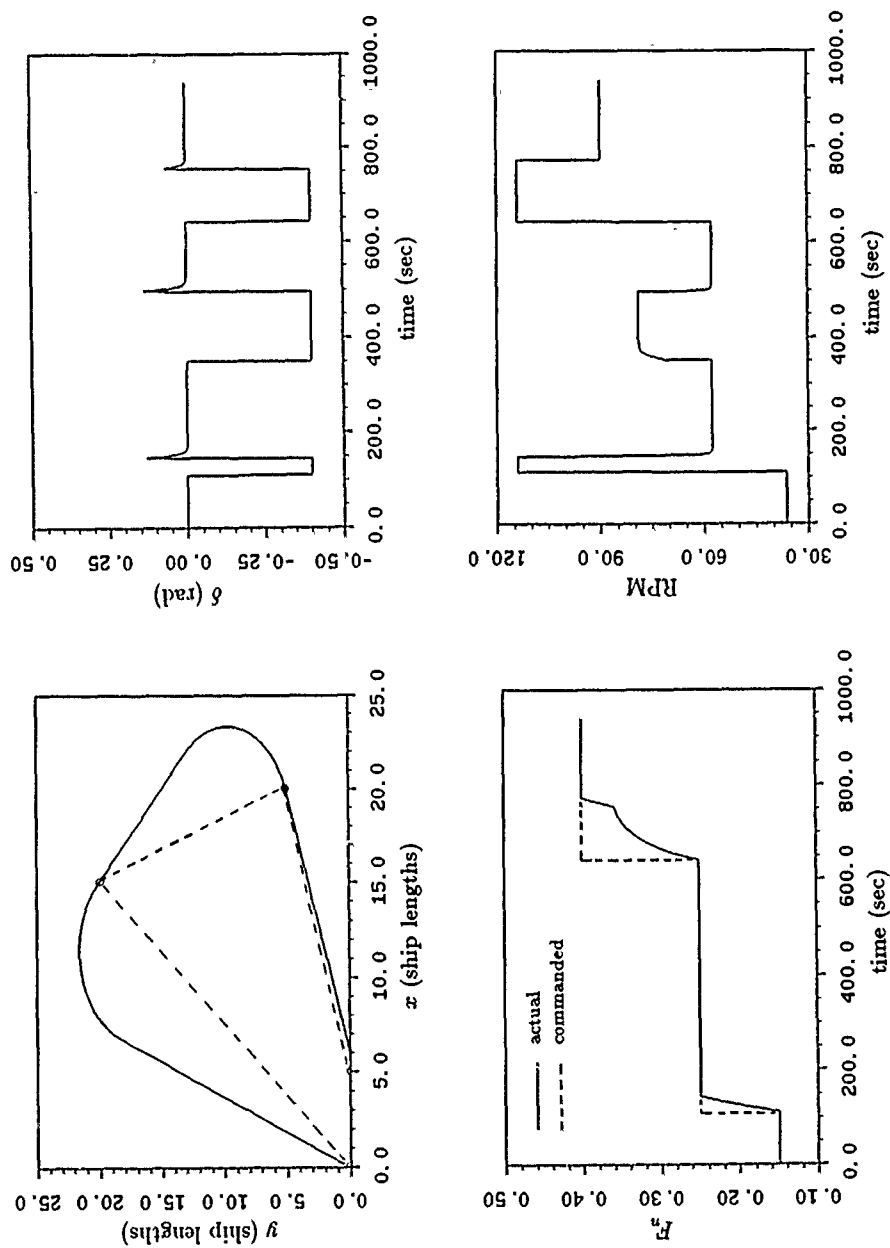


Fig. 4. Path tracking control: Nominal design.

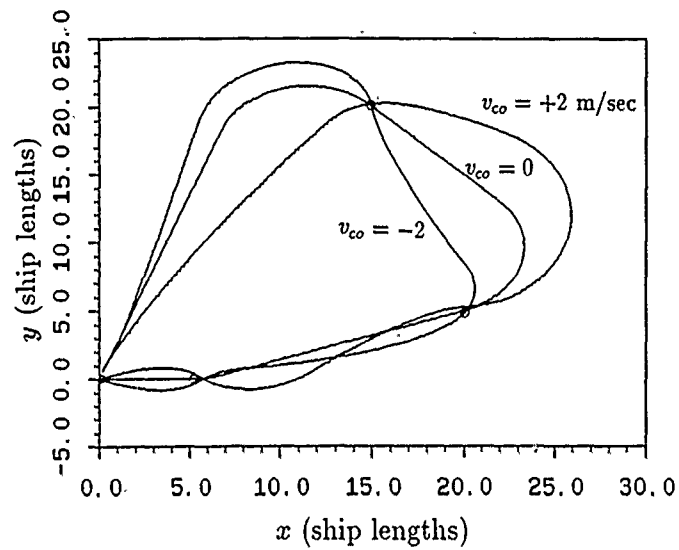


Fig. 5. Path tracking control: Current effect.

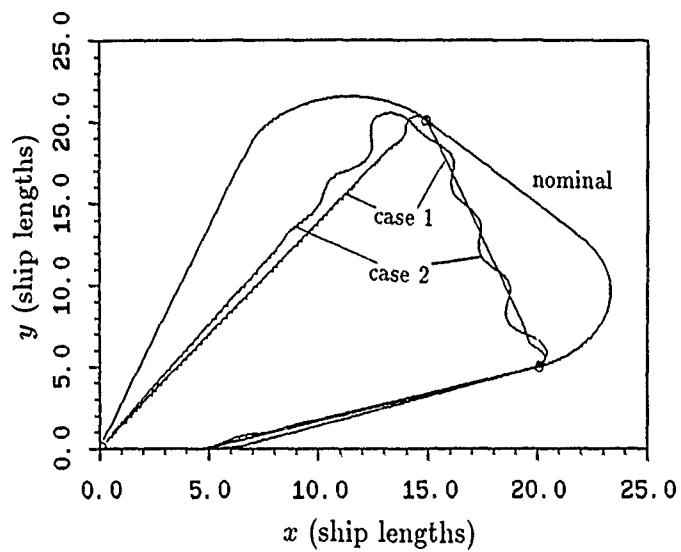


Fig. 6. Path tracking control: Robustness test.

increased to  $2Y_\delta$  and  $2N_\delta$ . Both of these changes lead to a vehicle less damped and more responsive.

- Case 2: Nominal control law with ship coefficients changes of  $0.1Y_v$ ,  $0.1N_r$ ,  $0.75Y_\delta$ , and  $0.75N_\delta$ . This corresponds to a less damped but also less responsive ship.

The results of Figure 6 demonstrate the ability of the controller to meet its mission requirements even under unrealistic errors in the design. It can also be concluded that if a cross track error autopilot needs to be implemented, a combination of line-of-sight navigator with a sliding mode steering controller can be used, where the design is based on higher values for  $Y_v$  and  $N_r$  and lower values for  $Y_\delta$  and  $N_\delta$ . Such an approach is based on underdesigning the system: the mathematical model is assumed to be less responsive and more heavily damped than the physical plant.

So far, perfect state measurement, with the exception of the sway velocity, has been assumed. A compass can provide the heading angle  $\psi$  and a rate gyro  $\dot{\psi}$ . Sensor noise in these measurements can be taken into account with the design of a Kalman filter without any major modifications in the controller design or the validity of the conclusions. The ship path keeping problem, however, requires knowledge of the lateral deviation off the design path; the system is unobservable unless the cross track error is measured. In the open sea this is equivalent to  $(x, y)$  position updates which are possible by an Inertial Navigation System (INS) and/or use of a Global Position System (GPS) receiver. Figure 7 shows a comparison between the nominal ship response and a trajectory obtained using a navigation time step or INS position updates every 60 secs. This corresponds to only 15 updates over the entire simulation run. Higher navigation time steps result also in stable response provided the target radius is appropriately increased. This demonstrates that the design leads to acceptable response even with the use of cheaper INS with lower position update rates.

Finally, the effects of varying the target radius (TR) are illustrated in Figure 8. The results confirm our earlier observations that increasing the target radius results in ship response that is closer to the straight line segments. Naturally, it is recommended that the target radius does not exceed the steady state turning radius of the ship.

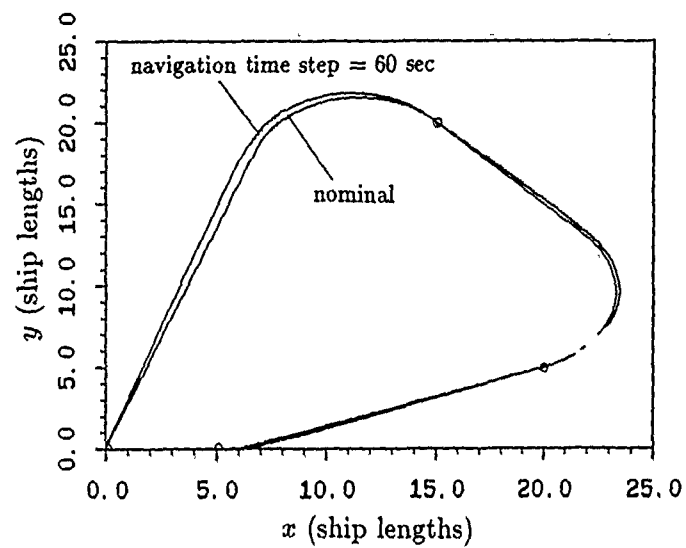


Fig. 7. Path tracking control: Navigational updates effect.

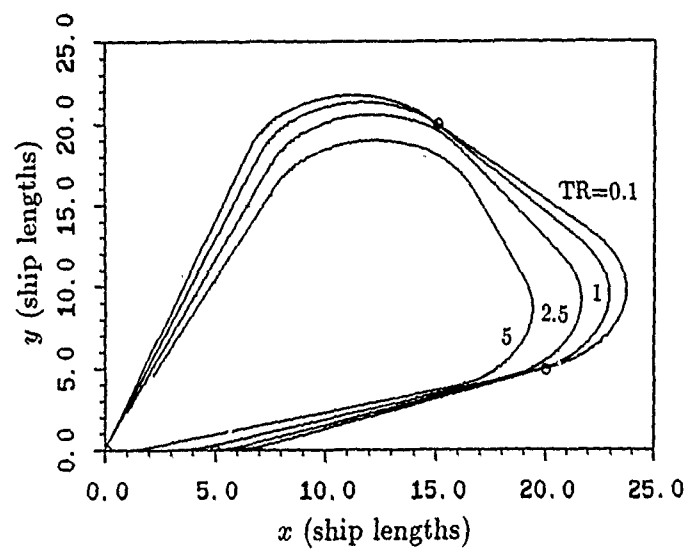


Fig. 8. Path tracking control: Target radius effect.

## 6. CONCLUSIONS

A methodology for designing multivariable sliding mode controllers for nonlinear systems, with special emphasis on ship maneuvering control has been developed. The method is suitable for a wide variety of non-linear control problems. In the present case of surface ship path keeping, the principal conclusions of this work can be summarized as follows:

- The controller proved to be very robust and was able to handle a wide range of parameter variations without any loss of stability.
- The sway velocity was shown to be insignificant from the point of view of automatic control, and therefore, its measurement or estimation is not necessary. This is in contrast to earlier results [4] which were based on simple first order lags representing the ship dynamics.
- A simple line-of-sight navigation scheme was proven to be very robust and allowed for controller/navigator separation in the design. This means that essentially the same controller can be used in confined or congested waters with a different sequence of way-points.
- INS position updates are needed but not necessarily at the same rate as the controller rate.
- The response of a cross track error controller can be simulated by appropriately underdesigning the system as explained in Section 5. This combines the advantages of a path keeping controller with the added robustness of a steering controller.
- The effects of constant disturbances can be minimized without the destabilizing effects of integral action or disturbance estimation and compensation.

Development of robust control and guidance laws for accurate path tracking in the presence of disturbances and sensor noise is the matter of ongoing research.

## 7. ACKNOWLEDGEMENTS

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SIMULATION: AN INTERFACE BETWEEN THEORY AND PRACTICE,  
ELUCIDATED WITH A SHIP'S CONTROLLABILITY STUDY

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1. ABSTRACT

Often there is a wide gap between research on man-machine performance under real life conditions and research on control behaviour in a laboratory context. The present study suggests to combine laboratory experiments within a strict axiomatic theoretical framework with less axiomatically constrained simulator experiments. Converging evidence from these two approaches should bridge the gap between the theoretical based laboratory experiment and the realism of the simulator experiment.

The idea is elucidated with the description of two experiments. In the first experiment the hypothesis is tested whether ship handler's control behaviour is mainly based on one of two elements: preprogrammed control or feedback control. Notions on preprogrammed control are primarily based on stimulus-related control setting. Notions on feedback control are primarily based on the evaluation of correctness of performance. The second (simulator) experiment is aimed at differences between the controllability of push-tows on inland navigation channels as a function of ship traffic density. The traffic density is varied to discriminate between performance based either on preprogrammed or feedback control. Results will show some advantages of this paired experiment approach.

2. INTRODUCTION

Attempts to measure human control activities vary from real life and field studies to simulator and laboratory experiments. In the case of ship control, various studies have provided information on the ship handler's control activities. These approaches have a serious common drawback in that they fail to consider a large number of variable factors which affect control behaviour.

In the present study, results from a simulator experiment approximating real-life conditions are combined with a laboratory experiment. Their combination may facilitate the generalization and interpretation of results.

Simulator experiments are usually rather complex. The implicit background is that because of the complexity of the real-life control task, the simulated task should be at least as complex in order to be realistic. It is hoped that

the realism obtained renders the generalization from simulator to real-life conditions acceptable. Yet from an experimental viewpoint, this approach leads to a lack of control of a number of variables which, in turn, puts at least some constraints on the interpretation of the results. The laboratory experiment, on the contrary, enables interpretations about the effects of system elements, but generalization of the laboratory results to the actual situation is more dubious.

To effectuate the advantages of the separate experiments, it is suggested to combine laboratory experiments within a strict axiomatic theoretical framework with less axiomatically constrained simulator experiments. Converging evidence from these two approaches should bridge the gap between the more abstract laboratory experiment and the realism of the simulation.

The idea of carrying out pairs of related experiments seems to be highly relevant for studying the ship handler's control behaviour. On the one hand there is the need of testing hypotheses on control behaviour within a constrained framework, on the other hand there is a gap between the generalization of experimental results on the interpretation of navigational performance.

The present study is aimed at investigating the controllability of ships. The first experiment (A) is focused on human behaviour in controlling a 40,000 ton container vessel. The second experiment (B) concerns push-tows travelling on the river "Waal" between Rotterdam and Duisburg. This experiment refers to a rather delicate question: the safety of push-tows on a narrow river. To define accurately ship manoeuvring tasks and since controllability of man-vehicle systems bears on control behaviour of humans, there was a need to investigate the quality of controllability within a tracking task paradigm. The experiment A will address control behaviour in a more axiomatic theoretical framework. The experiment B will hopefully bridge a gap between theory and practice. Both experiments will be described after a short introduction on the here following notion concerning the ship handler's control behaviour.

The notion is introduced that the ship handler's behaviour in controlling a ship in narrow or inland fairways is mainly based on feedback and to a minor extent on preprogrammed control. Feedback is effective when references for correctness of performance (perceptual memory) have been developed.

It is hypothesized that the ship handler develops with practice a motor and a perceptual memory. The motor memory contains the relationship between initial conditions, desired and past outcomes and rudder deflection specifications. The perceptual memory contains the relationship between initial conditions, past system outcomes and expected ship movements in the ship's environment (see Fig. 1) as perceived by the ship handler.

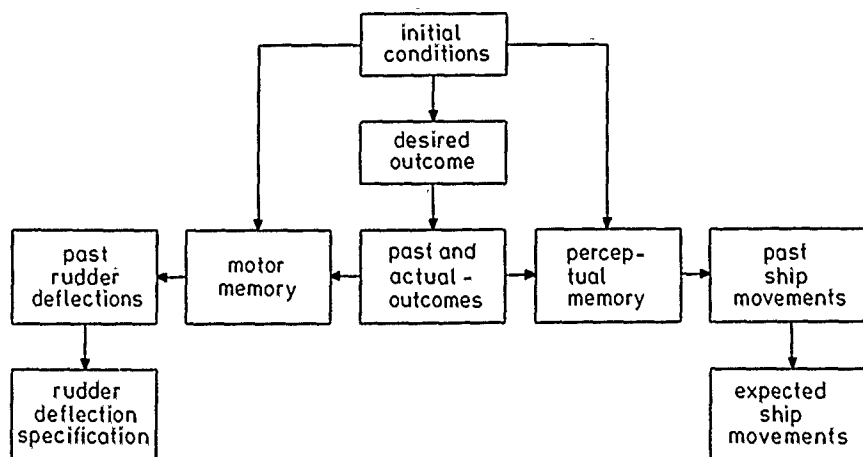


Figure 1 here

Figure 1. This diagram illustrates that rudder deflection specifications and expected ship movements are produced making use of information on initial conditions and desired outcomes. The motor memory and the perceptual memory relate information and production.

In tracking tasks, the perceptual memory is dominant. The subjects carry out motor memory-based rudder deflections. After watching the resulting ship's movements, they compare expected and actual movements. The role of the motor memory is to produce small adjustive movements, which are subsequently controlled by the perceptual memory by comparing expected and actual outcomes. In early learning, track completion depends fully on KR<sup>1</sup> because this provides the

<sup>1</sup>Knowledge of results is conceived of as information for the learner about proficiency of (control) activities for reaching desired goals. In case of ship tracking, it can be argued that in the early learning phase subjects aim at certain points of a fairway to keep the vessel on track as good as possible. The subjects improve tracking accuracy with practice by selecting references such as aimpoints on fairway edges and turn rates at various track positions which enable them to minimize deviations between the desired track and the path travelled. By doing so, each passage of a fairway provides knowledge of results by evaluating the control activities, the actual performance and the desired correctness of performance. References leading to correct passages are stored and they ultimately compose the perceptual memory. Orientation, as well as tracks and velocities, contribute to a build-up of a perceptual memory.

only means through which the subjects are informed about deviations between desired track and travelled path. Without KR performance does not improve, since the perceptual memory cannot develop. If KR is withdrawn after a training period, performance remains at the same level because the correctness of the travelled path cannot totally be inferred from the final position reached, but needs KR about the path itself.

Principally, the perceptual memory is based on peripheral feedback and hence is relatively slow while the motor memory is based on central programming which make relatively rapid actions possible. This means that accurate tracking performance in rapid<sup>2</sup> (or semi-slow) tasks should be based on motor memory and in slow tasks on perceptual memory.

### 3. EXPERIMENT A: ACCURACY OF PERFORMANCE IN VARIOUS TRACKING TASKS

#### 3.1 Introduction

The hypothesis is tested whether subjects increasingly need to base their control actions on a motor memory as a manoeuvre approximates a semi-slow task and, in the contrary, increasingly need to base actions on a perceptual memory when a manoeuvre approximates a very slow task<sup>2</sup>. It is suggested that within a range of tracking tasks (semi-, slow and very slow tasks), performance could be distinguished that purely should be based on perceptual memory in very slow tasks and that should be based to a certain extent on a motor memory in semi-slow tasks. Such tasks can be defined by forcing functions representing lane shifts, at short, medium and at long range (see Fig. 2).

The present experiment had three forcing functions and three KR-conditions as independent variables and manoeuvring accuracy as dependent variable. The forcing functions represented a semi-slow, a slow, and a very slow task. The three KR-conditions had the following characteristics. In condition KR-S, subjects generated their own KR. In condition KR, subjects were instructed to use references and were provided with KR over the path travelled. In condition C, the correct (reference) track was continuously visible on the sea-surface during a trial.

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<sup>2</sup>Rapid, semi-slow, slow and very slow (tracking) tasks are defined relative to the dynamic of the vessel under concern. These tasks provide, with regard to the manoeuvring characteristics of the vessel, respectively no, little, moderate and much possibility for the ship handler to correct errors in control-settings.

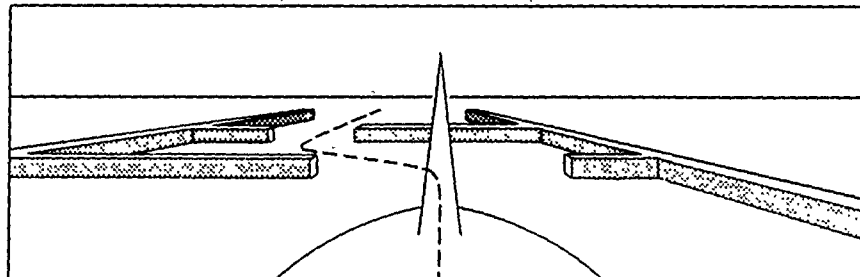


Figure 2. Definition of a forcing function by means of dikes. The forcing function is viewed through the windows of the bridge mock-up. In the foreground, the mast and the forward deck are visible. The desired track of the lane-shift is indicated by a dotted line. The line is only visible in the C-conditions.

Concerning the semi-slow task, it was expected that, relative to a slow task, subjects need to base their control actions more on motor memory. This means in condition C that subjects will perform in the semi-slow task as accurate as in the slow task. If performance, however, cannot be based on motor memory, subjects will show inaccurate manoeuvres relative to the slow task, because feedback control in rapid and semi-slow tasks will introduce delays in control and hence tracking errors.

In condition KR, performance is not supposed to differ from condition C, since subjects, instructed to use aimpoints as references, will perform as accurately as in condition C. Particularly, since the aimpoints on the route sections are at shorter distance in a semi-slow task, and accurate performance is expected.

In condition KR-S, performance will be degraded relative to the slow task because of a lack of references. Moreover, when references cannot contribute considerably to performance because feedback cannot effectively function, quality of manoeuvring will tend towards the inaccuracy of the other conditions.

The standard deviation of the rudder deflections in all three conditions will show larger values relative to the slow task because of the larger course alterations to be made. Condition C will show, relative to the other conditions, the largest standard deviations, since in this condition the tracking-error is most clearly shown.

Concerning the very slow task, it was expected that, relative to a slow task, subjects need to purely base control actions on a perceptual memory. This means in condition C that subjects will perform with the highest possible accuracy. The desired track in a very slow task tends towards a straight course and

tracking accuracy will, relative to a slow task, increase. In a slow task, however, performance is supposed to be based also on perceptual memory and hence when the reference track is visible, will show already the maximal tracking accuracy.

In condition KR, performance could differ from condition C with regard to the use of aimpoints. The same number of aimpoints in the slow task were used in the very slow task. Each aimpoint could be used at a certain distance from the dike opening. Since larger distances in the very slow task will introduce more variability, manoeuvring accuracy will tend to decrease.

In condition KR-S, performance will be degraded relative to the slow task because of the lack of references. Since in the very slow task the accuracy of perceptual memory is of major importance, it is expected that in this condition the largest tracking errors will be found since the reference cannot be accurate.

The standard deviation of the rudder deflections in all three conditions will show smaller values relative to the slow task because of the smaller course alterations to be made. Condition C will again show, relative to the other conditions, the largest deviations.

### 3.2 Method

Task: The ship, a 40.000 ton container vessel, travelled at an initial constant speed of approximately 10 knots and a constant number of shaft revolutions on a straight course. The subjects should shift to a parallel course at a distance of 333 m. The change should be terminated within a distance of 888 m, 1332 m or 2664 m (see Fig. 2). The forcing function with 888 m between the dikes represented a semi-slow manoeuvre, the forcing function with 1332 m between the dikes represented a slow manoeuvre and the third forcing function represented a very slow manoeuvre.

In condition C, the forcing function was visible as a black curve on the sea surface. In condition KR, the subjects were instructed to use three aimpoints on the route as references and the subjects were provided with KR over the travelled path. In condition KR-S, the subjects had to select references themselves and provided their own KR by observing the success of their passages.

Experimental design: Two factors were combined in the experimental design. The factor KR (3 levels) was varied between subjects. Each subject repeated four trials on a forcing function. Forcing function (3 levels) was varied within subjects (7 levels).

Instrumentation: The subject was seated in a chair in front of the centre window with a view on the fairway (see Fig. 2), generated by video-technique. The subject had a tiller available for adjusting rudder deflections within the limits of 35° port and starboard.



Procedure: All subjects participated for four hours during the morning or the afternoon. They were practised for about 45 minutes. Thereafter they performed on the slow task 23 trials, which took approximately 120 minutes. These trials were followed by two blocks of 4 trials on the other tasks. The subject first performed on the semi-slow and thereafter on the very slow task.

#### Scoring and analysis:

RMS: the root-mean-squared error as a measure to indicate the deviation between desired track and path travelled in meters.

$l_x$ : phase-shift in the direction of the fairway axis as a measure to indicate lead or lag of the path travelled relative to the desired track in meters.

$\sigma$ : standard deviation of the rudder deflection to indicate the deviation from the average rudder deflection in degrees.

The scores were subjected to an Analysis of Variance (ANOVA).

### 3.3 Results

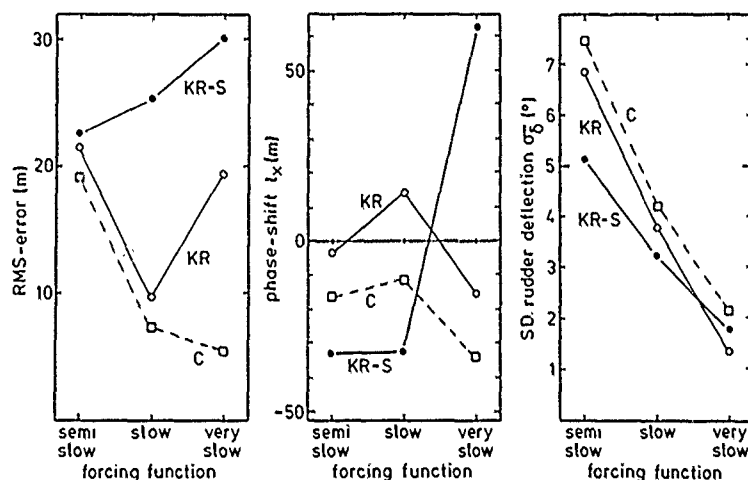


Figure 3. The RMS-error, the phase-shift  $l_x$  and the standard deviation of the rudder deflection as a function of KR-conditions and forcing functions, averaged over subjects.

The RMS-error showed a significant main factor KR ( $F = 18.5$ ;  $df = 2,18$ ;  $p < .01$ ) and a significant main factor forcing function ( $F = 5.6$ ;  $df = 2,36$ ;  $p < 0.001$ ). The significant interaction between KR and forcing function showed accurate tracking in condition C at the slow task and at the very slow task (see Fig. 3).

The phase shift  $l_x$  only showed a significant interaction between KR and forcing function ( $F = 3.1$ ;  $df = 4,36$ ;  $p < .05$ ) at the very slow task, the condition KR-S differed from the other conditions ( $p < .05$ ) (see Fig. 3).

The standard deviation of the rudder deflection showed significant main factors. The factor KR ( $F = 5.2$ ;  $df = 2,18$ ;  $p < .05$ ) showed highest values in the condition C (see Fig. 3). The factor forcing function ( $F = 134.0$ ;  $df = 2,36$ ;  $p < .01$ ) showed lowest values in the very slow forcing function. The significant interaction between KR and forcing functions showed as the semi-slow task largest deviations in the C- and KR-conditions.

### 3.4 Discussion

Semi-slow tasks: At the forcing function representing the semi-slow task, tracking accuracy showed large RMS-error. As this error is, particularly in condition C, significantly larger than at the slow and very slow task, it can be concluded that feedback control cannot be used effectively and cannot be enhanced by control based on motor memory. This result confirms the expectation that semi-slow tasks cannot be performed accurately when no accurate motor memory is available, since feedback control cannot be used effectively in such tasks.

As expected, performance in conditions KR and KR-S show similar results and parallel the expectations on ineffective use of feedback.

Use of the rudder, as reflected by the standard deviation of the rudder deflections, is in line with the expectation.

Very slow tasks: At the forcing function representing the very slow task, tracking accuracy was high in condition C, medium in condition KR and low in condition KR-S. This is in full agreement with the expectations.

In condition C, a highly precise performance was expected. This performance could be slightly better (RMS-error) at the very slow task than at the slow task, since the forcing function, representing the very slow task, is minimally curved.

In condition KR, performance is not as precise as in condition C because of the insufficient support of aimpoints at the route-sections but not as imprecise as in condition KR-S with the lack of references.

Results confirm the expectation that tracking accuracy in very slow and slow tasks depend on the accuracy of perceptual memory or instructed references for evaluating correctness of performance.

Rudder use is in line with the expectation.

#### 4. EXPERIMENT B: DIFFERENCES IN THE CONTROLLABILITY OF PUSHTOWS

##### 4.1 Introduction

With regard to the introduction of six-barge pushtows on the inland waterways between Rotterdam and Duisburg, a simulator experiment was conducted<sup>3</sup>. It was expected that relative to four-barge pushtows, six-barge pushtows would improve economy of transport and questions arose on the safety of the controllability of these larger pushtows.

It was decided to compare performance of four and six-barge pushtows by means of simulator experiments under critical environmental conditions with the performance of a four-barge pushtow as a standard.

The critical environmental conditions were composed of factors such as wind, fairway width, fairway geometry and traffic density. In the present experiment, traffic density was an independent variable, while passing distance and standard deviation of the rudder deflection were dependent variables.

Traffic density was matched on the findings discussed in experiment A. It was organized in such a way that dense traffic situations resembled semi-slow tasks and situations with only a sprinkling of boats on the river resembled slow tasks.

It was expected that due to the larger beam of the six-barge pushtow, passing distances would decrease stronger as a function of increasing traffic density than passing distances of the four-barge pushtow because of the relative lesser possibility for correcting control setting errors with six-barge pushtows in semi-slow tasks. Since the dynamic characteristics of both vessels tend to be the same, it was expected that the standard deviation of the rudder deflection would increase as a function of increasing traffic density. As shown in experiment A, if control behaviour should be based on motor memory, performance becomes inaccurate and requires more control corrections resulting in larger standard deviations. Since the six-barge pushtow will have relatively lesser possibility for correcting control setting errors, particularly in semi-slow tasks, a higher standard deviation of the rudder deflection may be expected.

##### 4.2 Method

Task: The subjects were asked to control a four-barge or a six-barge empty pushtow, downstream with a groundspeed of 22 km/h. In each trial the vessel passed a river bend with a critical radius and a riverwidth of approximately 150 m. Other vessels, composing the traffic density and the fairway, were visible through the bridge mock-up on a projection screen and on a simulated radar picture (see Fig. 4). traffic was varied in a left (L) and a right (R)

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<sup>3</sup>Research under contract to the Rijkswaterstaat, Dienst Verkeerskunde, Dordrecht, the Netherlands.

bend between no (O), low (A), moderate (B) and high density (C, D). The wind-force amounted to Bf 5, there was moderate visibility and the winddirection was right across the route.

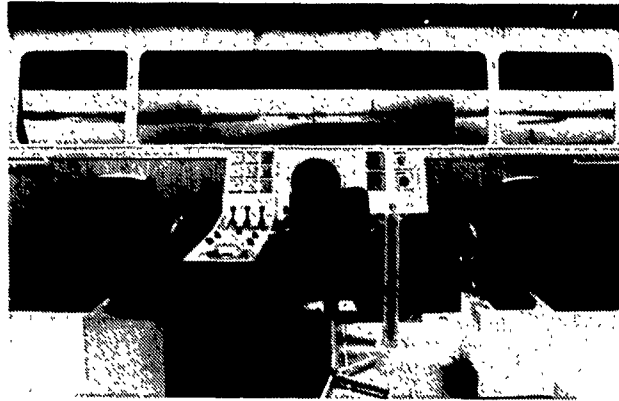


Figure 4. Console with displays and controls and at the middle a position for the subject.

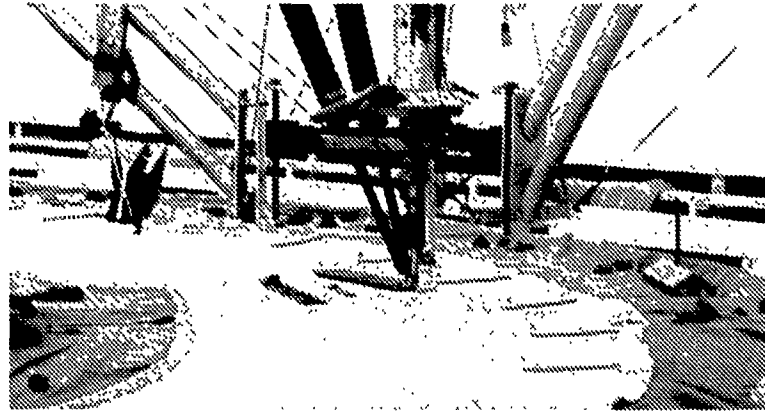


Figure 5. View on the model board with TV-cameras hanging above a model of the river with moving models of the other vessels.

Experimental design: Two factors were combined and varied within subjects. The factor pushtow was varied on two levels, the factor traffic density was varied on seven levels.

Instrumentation: A subject was seated at the centre window of the bridge mock-up of the simulator. He had control over the main rudders, the flanking and bow-rudders and the propeller revolutions (see Fig. 4). The images, projected around the bridge mock-up were generated in a model board with moving models of other vessels (see Fig. 5).

Procedure: Each subject was tested on two successive days. Each day each subject spent four hours at the simulator. The subjects performed one hour by turn. Each trial took 10 minutes. Each subject performed 12 trials.

#### Scoring and analysis:

SB: minimal distance in meters at starboard between the pushtow and other vessels or objects.

SD: standard deviation in degrees of the main rudder (other performance indicator are neglected here).

The scores were subjected to an analysis of variance (ANOVA).

#### 4.3 Results

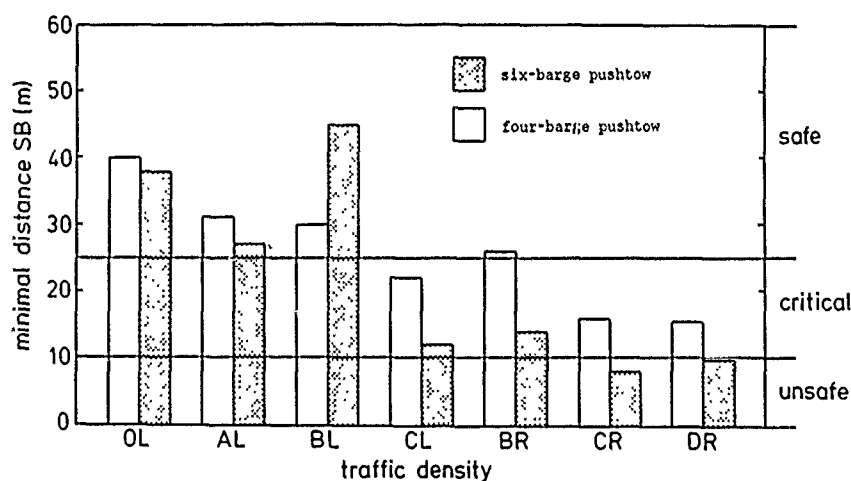


Figure 6. The minimal passing distance at starboard as a function of pushtow and traffic density, averaged over subjects.

The SB showed the significant main factors pushtow ( $F = 19.9$ ;  $df = 1,11$ ;  $p < .01$ ) and traffic density condition ( $F = 34.1$ ;  $df = 6,66$ ;  $p < .01$ ). The significant interaction between pushtow and traffic condition showed differences between the pushtows at traffic density condition BL, CL, BR and CR (see Fig. 6).

The SD showed the significant main factors pushtow ( $F = 50.8$ ;  $df = 1,11$ ;  $p < .01$ ) and traffic density conditions ( $F = 15.7$ ;  $df = 6,11$ ;  $p < .01$ ). The significant interaction between pushtow and traffic density conditions showed differences between pushtow and traffic density conditions BR, CR and DR (see Fig. 7).

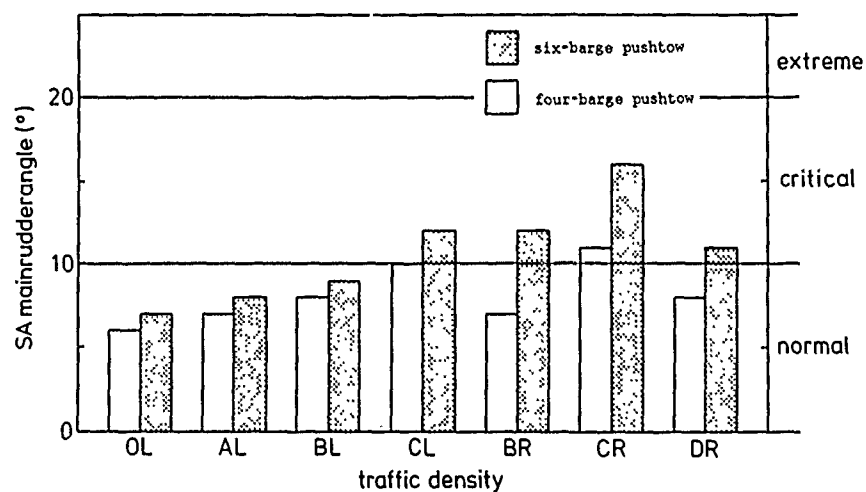


Figure 7. The standard deviation of the rudder deflection as a function of pushtow and traffic density, averaged over subjects.

#### 4.4 Discussion

The trend of decreasing minimal starboard passing distances as a function of increasing traffic density parallels the expectation. Both, in the left and the right bend, this passing distance shows the same trend. There is an unexpected effect at the traffic density condition BL; the six-barge pushtow shows a larger passing distance than the four-barge pushtow. Examination of other parameters revealed that in this condition captains systematically decreased speed a little bit. As a matter of fact, they violated the instructions, but due to practice, in this condition a very small speed reduction helps a lot to smooth the manoeuvre.

The results showed similar performance with both pushtows at the conditions OL and AL and at DR. At the conditions CL, BR and CR, performance significantly differed between both pushtows and it had to be decided to characterize the controllability of six-barge pushtows under that conditions as unsafe.

The standard deviation of the rudder deflection also parallels the expectations and supports that performance is critical with six-barge pushtows at the conditions BC and CR.

#### 5. FINAL REMARKS

The results of both experiments showed converging evidence with regard to decreasing performance quality as a function of decreasing possibility for correcting errors in control setting. As indicated by the results of experiment A, if subjects increasingly need to base control behaviour on motor memory as a manoeuvre approximates a semi-slow task, performance tends to inaccuracy. The traffic density conditions in experiment B were designed to match such a range of manoeuvring tasks. The condition C of experiment A most closely resembled the conditions of experiment B. The reference provided on the watersurface in condition C was to a certain extent available in the form of riverbanks in experiment B. Results in condition C particularly showed decreasing accuracy with increasing need for motor memory.

The results of experiment B at the condition BL illustrates well the weakness of a less axiomatically constrained simulator experiment. On behalf of the contractor and to improve the validity of the experimental set-up, the manoeuvring task was self-paced. It provided a better match between test and real life conditions, however, because of a lack of control on the manner how the instructions were followed, interpretation of results is dubious.

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- (2) H. Schuffel, "Human Control of Ships in Tracking Tasks", Ph.D. Thesis, TNO Institute for Perception, Soesterberg, 1986.
- (3) H. Schuffel, J.P.A. Boer, and L. van Breda, "Differences in the controllability of four and six-barge pushtows". TNO Institute for Perception, Soesterberg, 1987 (to be published).

## PROPULSION CONTROL SIMULATION USING LOW-COST SPREADSHEET PROGRAMS

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### 1. ABSTRACT

Traditionally, control system simulation programs are written in a high-level language such as FORTRAN by experienced engineers and programmers and are run on main-frame or mini-computers. Many of these programs can now be programmed as well as operated on today's standard personal computers with good performance. These simulation programs can generate quality, high-resolution graphic system simulation response curves on a color monitor (CRT). Hard-copy printouts of the input program, output data and response curves can be produced by a printer or plotter.

Experienced propulsion control system engineers in general are highly skilled in analog control theory but have little or no programming experience. Off-the-shelf simulation programs are available but are often too specialized, restrictive, difficult to use, and can be expensive.

Simulation of ship propulsion control systems can be accomplished on personal computers using low-cost spreadsheet programs. And with the addition of a real-time data acquisition front-in system to a personal computer, digitized response data from the system can be imported into the simulation spreadsheet and a comparative analysis can be performed. From this analysis, the simulation model and or parameters can be validated. The complexity of the model can be adapted to meet the requirements analysis objectives.

This paper describes how spreadsheet programs running on a personal computer can be used for propulsion control system simulation. Knowledge of computer programming is not required. The spreadsheet format and equations are described and a number of examples (from very simple to complex) are listed, run, plotted and explained.



## 2. CONTROL SYSTEM BASICS

### 2.1 First and second-order transfer functions

A block diagram representation of a simple first-order (one real pole), lowpass transfer function is shown in Fig. 2-1. In the complex frequency domain  $s$ ,  $X(s)$  is the input to the system and  $Y(s)$  is the output response.

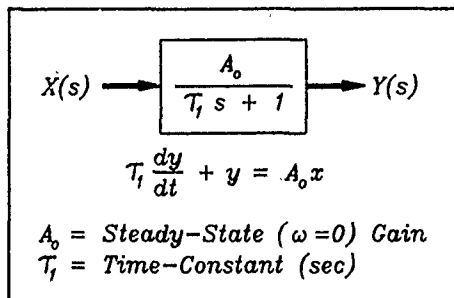


Figure 2-1. First-order system.

In the time domain,  $x(t)$  is the input and  $y(t)$  is the time response as represented by the systems differential equation shown in Fig. 2-1. This system has a single time-constant and has a steady-state, low-frequency, open-loop gain represented by  $A_o$ . The system transfer function is given by

$$T(s) = \frac{Y(s)}{X(s)} = \frac{A_o}{\tau_1 s + 1} \quad (1)$$

or

$$\tau_1 s Y(s) = A_o X(s) - Y(s)$$

$$Y(s) = \frac{1}{\tau_1 s} [A_o X(s) - Y(s)] \quad (2)$$

An equivalent block diagram representation of this system is shown in Fig. 2-2. This model is constructed from very basic functional blocks such as subtractor and scaling blocks and an integrator block.

A damped second-order system with real and distinct, open-loop poles is shown in Fig. 2-3a. This system can be represented as two cascaded first-order systems as shown in Fig. 2-3b. Each of these first-order sections could be represented by the configuration shown in Fig. 2-2.

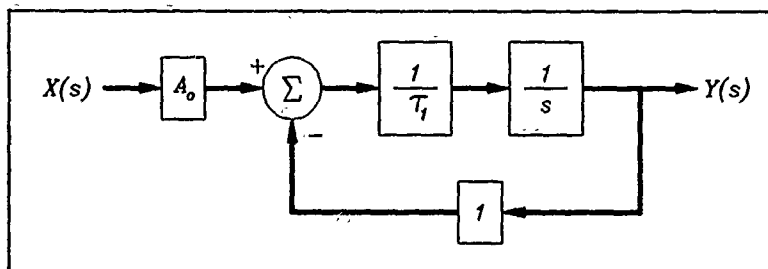


Figure 2-2. First-order model using basic functional blocks.

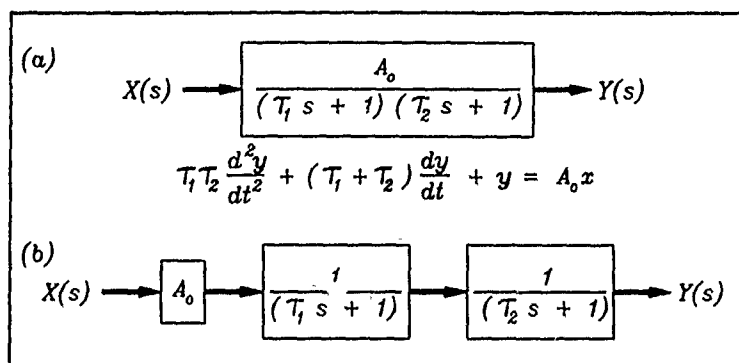


Figure 2-3. Damped second-order system.

An under-damped second-order system is shown in Fig. 2-4. Note that the denominator of the transfer function is shown in convenient un-factored form because the open-loop poles are complex.

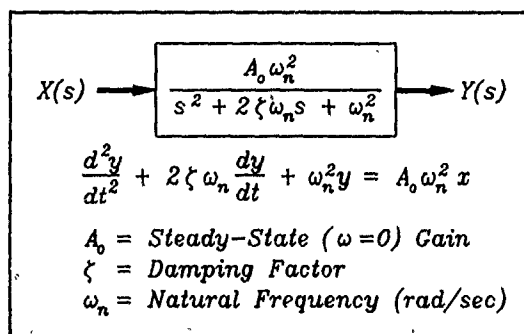


Figure 2-4. Under-damped second-order system.

The damping factor  $\zeta$  and natural frequency  $\omega_n$  are useful parameters in evaluating the performance of a system. Whereas, the locations of the poles (roots of the denominator) in the  $s$ -plane are less useful when evaluating the performance of actual electro-mechanical systems. System step (time) and frequency response measurements can be used to determine these parameters. It should be noted that if the damping factor is increased enough, the roots will become real and the model shown in Fig. 2-3 should be used. The system transfer function is given by

$$T(s) = \frac{Y(s)}{X(s)} = \frac{A_o \omega_n^2}{s^2 + 2\zeta \omega_n s + \omega_n^2} \quad (3)$$

Rearranging and solving for  $Y(s)$  yields:

$$Y(s) = \frac{1}{s} \frac{1}{s} [A_o \omega_n^2 X(s) - 2\zeta \omega_n s Y(s) - \omega_n^2 Y(s)] \quad (4)$$

This system can also be represented using the aforementioned basic functional blocks (see Figs. 2-1 and 2-2) as shown here in Fig. 2-5. With this *state-variable* representation, the system's output position ( $Y$ ), velocity ( $sY$ ) and acceleration ( $s^2Y$ ) can be observed.

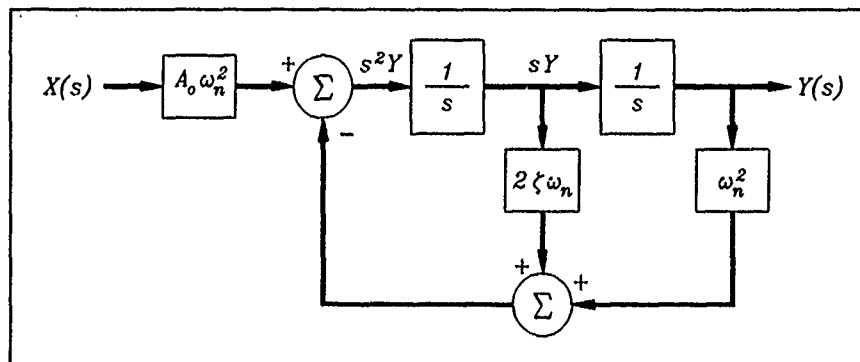


Figure 2-5. Under-damped second-order system using basic functional blocks.

In summary, odd or even,  $n$ th-order systems can be modeled by cascading a combination of simple 1st and 2nd order transfer functions. These simple low-order functions can then be further simplified by using the aforementioned basic functional blocks such as scaling, subtracting and integrating blocks. Scaling and subtracting are the simplest mathematical operations and are easily implemented in spreadsheet programs. Integration is much more complex, but can be approximated using numerical methods and can be applied in spreadsheets as well.

## 2.2 Numerical integration

The basic integration functional block appearing in previous figures is shown here in Fig. 2-6.

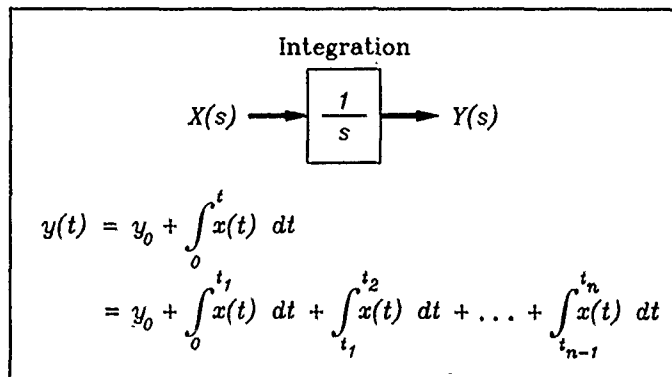


Figure 2-6. Integration function block.

The input is some time-dependent function represented by  $x(t)$  and the integral output is represented by  $y(t)$ . The constant  $y_0$  is the initial value or condition of the integration at time  $t=0$ . As shown, the total integration from time  $t=0$  to some time  $t$  can be divided into  $n$  segments. As shown in Fig. 2-7,  $y(t)$  is equivalent to the area under the  $x(t)$  curve. In this example, it is assumed that the initial condition or area under the curve  $y_0=A_0=0$ .

The input  $x(t)$  is sampled at each time increment  $t_i$  and the area  $A_i$  is determined and is added to the previous cumulative area. As shown in the figure, the actual  $x(t)$  may be a smooth function, but is only sampled at times  $t_i$ . Hence, the sampling rate will directly affect the accuracy of this approximation method for determining the area under the curve. The sampling rate must be much greater than the maximum slew rate of  $x(t)$  for good results. That is, as the slew rate of  $x(t)$  increases, more area segments are required per unit time. If the sampling rate is fixed, then the time sampling step is constant and equal to  $\Delta t = t_i - t_{i-1}$ . In simple terms,  $y(i)$  can be expressed as:

$$y_{new} = y_{old} + \frac{\Delta t}{2} (x_{old} + x_{new}) \quad (5)$$

Hence,  $x(t)$  is sampled every  $\Delta t$  seconds, the old and new values of  $x$  are determined, added and then multiplied by  $\Delta t/2$ . This incremental area is then added to the old value (cumulative value) of  $y$ . These operations can be easily implemented by setting up a simple table consisting of 3 columns designated:  $t$ ,  $x(t)$  and  $y(t)$  as illustrated in Table 2-1.

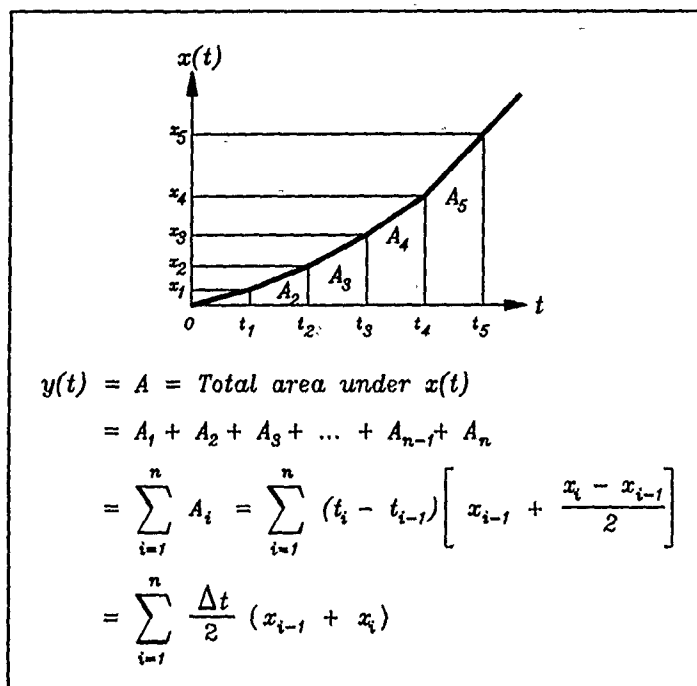


Figure 2-7. Numerical integration.

Table 2-1. Numerical integration columns.

$t$	$x(t)$	$y(t)$
.....	.....	.....
$t_0$	$x(t_0)$	$y(t_0)$
$t_1$	$x(t_1)$	$y(t_1)$
$t_2$	$x(t_2)$	$y(t_2)$
$t_3$	$x(t_3)$	$y(t_3)$
$t_4$	$x(t_4)$	$y(t_4)$
$t_5$	$x(t_5)$	$y(t_5)$

For example, the integral of  $x(t)$  from time  $t_0$  to time  $t_5$  is evaluated as follows:

$$\begin{aligned}
 y(t_1) &= y(t_0) + \frac{\Delta t}{2} [x(t_0) + x(t_1)] \\
 y(t_2) &= y(t_1) + \frac{\Delta t}{2} [x(t_1) + x(t_2)] \\
 y(t_3) &= y(t_2) + \frac{\Delta t}{2} [x(t_2) + x(t_3)] \\
 y(t_4) &= y(t_3) + \frac{\Delta t}{2} [x(t_3) + x(t_4)] \\
 y(t_5) &= y(t_4) + \frac{\Delta t}{2} [x(t_4) + x(t_5)]
 \end{aligned} \tag{6}$$

The integration starts at time  $t_0$  and  $x(t_0)$  and  $y(t_0)$  are the initial values of the input and output, respectively. Note that this table consists of 3 columns and 6 rows. Additional rows could be added as required to extend the time of integration or to increase the sampling rate (samples per second) for a fixed duration.

It is important to note that the equation or formula for  $y$  in each row is the same formula as in the preceding row except that the subscripts are incremented by one. This is a very important feature because in spreadsheet programs formulas can be copied from a row to one or more rows (range of rows). The copying utility provides for the automatic incrementing of cell addresses of the input data cells that are used when calculating the formula. Therefore, the formula for  $y$  in this example need be entered only once, at  $y(t_1)$ . The remaining equations or formulas are entered by copying the equation from  $y(t_1)$  to  $y(t_2) \dots y(t_n)$  as required.

### 2.3 First-order system modeling with numerical integration

The input  $x_1(t)$  to the integrator in the first-order system shown in Fig. 2-2 is

$$x_1(t) = \frac{1}{\tau_1} [A_o x(t) - y(t)] \tag{7}$$

and the output  $y(t)$  is the integral of  $x_1(t)$ . Substituting (7) into (5) gives:

$$y_{new} = y_{old} + \frac{\Delta t}{2} (\dot{x}_{i_{old}} + \dot{x}_{i_{new}}) \quad (8)$$

This calculation can be easily determined by setting up a simple table (similar to Table 2-1) consisting of 4 columns designated  $t$ ,  $x(t)$ ,  $x_i(t)$  and  $y(t)$  as illustrated in Table 2-2.

Table 2-2. 1st order table.

$t$	$x(t)$	$x_i(t)$	$y(t)$
$t_0$	$x(t_0)$	$x_i(t_0)$	$y(t_0)$
$t_1$	$x(t_1)$	$x_i(t_1)$	$y(t_1)$
$t_2$	$x(t_2)$	$x_i(t_2)$	$y(t_2)$
$t_3$	$x(t_3)$	$x_i(t_3)$	$y(t_3)$
$t_4$	$x(t_4)$	$x_i(t_4)$	$y(t_4)$
$t_5$	$x(t_5)$	$x_i(t_5)$	$y(t_5)$

As an example, the output of a first-order system evaluated at time  $t_5$  can be calculated as follows:

$$\begin{aligned}
 x_i(t_1) &= \frac{1}{\tau_1} [A_o x(t_1) - y(t_0)] & y(t_1) &= y(t_0) + \frac{\Delta t}{2} [\dot{x}_i(t_0) + \dot{x}_i(t_1)] \\
 x_i(t_2) &= \frac{1}{\tau_1} [A_o x(t_2) - y(t_1)] & y(t_2) &= y(t_1) + \frac{\Delta t}{2} [\dot{x}_i(t_1) + \dot{x}_i(t_2)] \\
 x_i(t_3) &= \frac{1}{\tau_1} [A_o x(t_3) - y(t_2)] & y(t_3) &= y(t_2) + \frac{\Delta t}{2} [\dot{x}_i(t_2) + \dot{x}_i(t_3)] \\
 x_i(t_4) &= \frac{1}{\tau_1} [A_o x(t_4) - y(t_3)] & y(t_4) &= y(t_3) + \frac{\Delta t}{2} [\dot{x}_i(t_3) + \dot{x}_i(t_4)] \\
 x_i(t_5) &= \frac{1}{\tau_1} [A_o x(t_5) - y(t_4)] & y(t_5) &= y(t_4) + \frac{\Delta t}{2} [\dot{x}_i(t_4) + \dot{x}_i(t_5)]
 \end{aligned} \quad (9)$$

The initial values in the first row at time  $t_0$  include:  $x(t_0)$ ,  $x_i(t_0)$  and  $y(t_0)$ . For a steady-state condition at time  $t_0$ ,  $A_o x(t_0) = y(t_0)$ ; therefore, the input to the integrator  $\dot{x}_i(t_0) = 0$ .

Only the formulas for  $x_i(t_1)$  and  $y(t_1)$  in the second row (row  $t_1$ ) need be entered into the spreadsheet; the remaining rows can be entered by copying the formulas from the second row. The values for  $x(t)$  can be manually entered one (row) at a time in the  $x(t)$  column. However, if the equation (formula) for  $x(t)$  is known, it can be entered at location  $x(t_0)$  and then copied to the remaining rows. To minimize the number of keystrokes when copying these formulas, simply copy all of the equations in row  $t_1$  to the remaining rows in one step, including an equation for  $t$ . In summary, the first row ( $t_0$ ) contains all the initial values and the second row ( $t_1$ ) contains the equations that will be copied into the remaining rows.

#### 2.4 Second-order system modelling using numerical methods

The second-order system shown in Fig. 2-3 can be modelled by cascading two first-order system blocks. Hence, the output of the 1st block  $y_1(t)$  is the input  $x_2(t)$  to the 2nd block. The table for this second-order system can be set up simply by adding two additional columns  $x_{12}(t)$  and  $y_2(t)$  to those of Table 2-2 as shown here in Table 2-3.

Table 2-3. 2nd-order table columns.

$t$	$x(t)$	$x_{11}(t)$	$y_1(t)$	$x_{12}(t)$	$y_2(t)$
$t_0$	$x(t_0)$	$x_{11}(t_0)$	$y_1(t_0)$	$x_{12}(t_0)$	$y_2(t_0)$
$t_1$	$x(t_1)$	$x_{11}(t_1)$	$y_1(t_1)$	$x_{12}(t_1)$	$y_2(t_1)$
$t_2$	$x(t_2)$	$x_{11}(t_2)$	$y_1(t_2)$	$x_{12}(t_2)$	$y_2(t_2)$
$t_3$	$x(t_3)$	$x_{11}(t_3)$	$y_1(t_3)$	$x_{12}(t_3)$	$y_2(t_3)$
$t_4$	$x(t_4)$	$x_{11}(t_4)$	$y_1(t_4)$	$x_{12}(t_4)$	$y_2(t_4)$
$t_5$	$x(t_5)$	$x_{11}(t_5)$	$y_1(t_5)$	$x_{12}(t_5)$	$y_2(t_5)$

Again, the first row ( $t_0$ ) contains the initial (steady-state) values for the system. The values for  $t_0$ ,  $x_{11}(t_0)$  and  $x_{12}(t_0)$  are zero and the initial value of the system input  $x(t)$  is  $x(t_0)$ . The steady-state values for  $y_1(t)$  and  $y_2(t)$  are determined as follows:

$$y_1(t_0) = A_{o1}x(t_0) \text{ and } y_2(t_0) = A_{o2}y_1(t_0) \quad (10)$$



The formulas for the second row (row  $t_1$ ) are as follows:

$$\begin{aligned} x_{i1}(t_1) &= \frac{1}{\tau_1} [A_{o1}x(t_1) - y_1(t_0)] & y_1(t_1) &= y_1(t_0) + \frac{\Delta t}{2} [x_{i1}(t_0) + x_{i1}(t_1)] \\ \text{and} & & & \\ x_{i2}(t_1) &= \frac{1}{\tau_2} [A_{o2}y_1(t_1) - y_2(t_0)] & y_2(t_1) &= y_2(t_0) + \frac{\Delta t}{2} [x_{i2}(t_0) + x_{i2}(t_1)] \end{aligned} \quad (11)$$

In conclusion, it is important to note that higher-order systems can be handled in the same method by simply adding two additional columns for each additional cascaded first-order section.

### 3. THE SPREADSHEET PROGRAM

#### 3.1 Introduction to spreadsheet formats

In general, a spreadsheet is arranged as a rectangular array of *cells* which can contain formulas, numeric data or text. Each cell has an address based on its physical location within the spreadsheet. Cell addresses are designated by *column* and *row* coordinates within the spreadsheet. Columns are assigned with upper case letters A, B, ..., AA, ... ZZ, where column "A" is the first column and is located at the left margin of the spreadsheet. Rows are designated with numbers 1, 2, ..., etc. and start at the top margin. Hence, the first cell address at the upper left-hand position is at location A1. The column *width* of all cells can be set to a default value (typically 9-character positions wide) or can be set to a particular width on an individual basis.

The cursor (highlighted cell on the screen) points to the current cell. The cursor's location can be moved using the *arrow keys* (up, down, right and left) or the address of the desired cell can be entered directly via the keyboard. When the cursor points to the desired cell, the data can then be entered using the keyboard.

In addition to displaying cell information, the spreadsheet screen shows column and row coordinates across the top and along the left-hand side of the spreadsheet area on the screen, respectively. These coordinates also become highlighted to indicate the current cell. The top line of the screen contains a "pull-down" menu which can be used to enter spreadsheet commands. The second line on the screen is the *Input Line* which displays data as it is entered from the keyboard or displays the cell address, attributes and contents of the current cell. Attributes include information such as numeric format, column width and font type. The bottom line displays status information relating to the entire spreadsheet such as file name, window number, etc.. It is important to note that when the spreadsheet is printed, only the spreadsheet cell contents are printed.

As mentioned previously, the Input Line on the screen displays the contents of the current cell or displays the information as it is entered by the keyboard. If the current cell contains a formula, the Input Line displays the

formula as it was entered; the results of the calculation (a number) is displayed at the current cell. For example, if the cursor is moved to cell A1 and the number "2" is entered, "2" is displayed at cell location A1. If the cursor is then moved to cell B1 and the number "4" is entered, "4" is displayed at cell location B1. And, if the cursor is then moved to cell C1 and the formula  $+A1*B1$  is entered, the calculated results "8" is displayed at cell C1.

### 3.2 Spreadsheet graphs and formulas

Spreadsheet programs provide for the plotting of graphs of data contained within the spreadsheet. Graphs can be displayed on the screen or can be printed on a printer or plotter. Various graph types can be plotted such as line graphs, bar graphs, XY graphs, pie charts and other special purpose graphs. The XY-type graph is used to plot  $Y$ , an output or response, versus an input  $X$ . Typically, a spreadsheet can plot up to 6 output series  $Y_1 \dots Y_6$  versus an input series  $X$ .

When plotting the time response of an analog system, the  $X$ -series is the time column  $t$  and the output response data are located in the column for the  $Y_1$ -series. For example, the vertical block of cells in the first column A1...A11 could be the  $X$ -series containing numbers 0 to 10 representing time from  $t=0$  to 10 seconds. The vertical block of cells in the next column B1...B11 could be the  $Y_1$  series where each cell contains the formula for  $y_1(t)$  or  $B(A)$ .

Table 3-1. Spreadsheet cell format.

Column Row	A	B
1	0	0
2	1	2
3	2	4
4	3	6
5	4	8
6	5	10
7	6	12
8	7	14
9	8	16
10	9	18
11	10	20

Table 3-2. Spreadsheet formulas.

Column Row	A	B
1	0	$2*A1$
2	$+A1+1$	$2*A2$
3	$+A2+1$	$2*A3$
4	$+A3+1$	$2*A4$
5	$+A4+1$	$2*A5$
6	$+A5+1$	$2*A6$
7	$+A6+1$	$2*A7$
8	$+A7+1$	$2*A8$
9	$+A8+1$	$2*A9$
10	$+A9+1$	$2*A10$
11	$+A10+1$	$2*A11$

Table 3-1 shows what would be displayed on the screen for this example. Again, column A indicates time and column B indicates the system response. The contents of columns A and B are shown in Table 3-2. These formulas are not displayed on the screen as shown here. The contents of individual cells, however, can be displayed on the *Input Line*.

Notice that formulas are used to generate the time data. That is, the time

for each row is 1 second greater than that of the previous row. The formula for time is entered only once at cell A2 and then it is copied to cells A3...A11. The spreadsheet program automatically increments the row numbers when copying in a column as illustrated here in this example. Similarly, the output data displayed in column B in Table 3-1 is calculated from the corresponding formulas contained in column B of Table 3-2. In this example, the output is a simple linear function of time, that is,  $B=2*A$ . Again, the formula is entered only once at cell B1 and then copied to cells B2...B11.

The graph for this example is plotted in Fig. 3-1. This graph is setup by using the spreadsheet /Graph command. This *Graph Type* is XY. The *X-Axis Series* can be selected by moving the cursor to cell A1 and then depressing the "." key to mark the beginning of the block to be selected. The cursor can then be moved downward to cell A11 and then depressing the <RETURN> key to mark the end of the selected block. The *1st Series* B1...B11 can be selected using the same method. The graph can be displayed at any time by depressing the function key "F10" or by depressing the View key while in the Graph menu. Finally, a grid and X and Y labels can be added to this graph as illustrated.

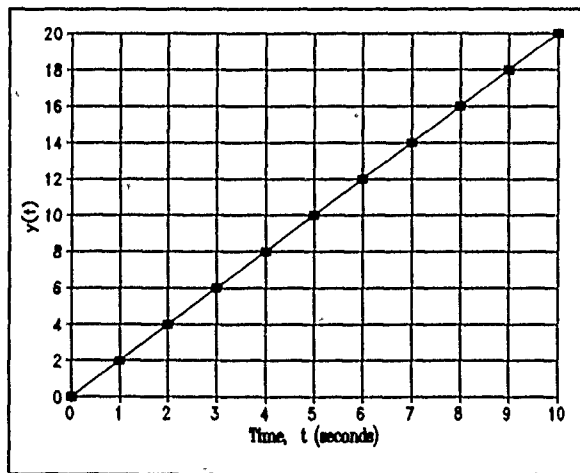


Figure 3-1. Spreadsheet XY-plot example.

#### 4. CONTROL SYSTEM SIMULATION USING THE SPREADSHEET PROGRAM

##### 4.1 First-order system simulation

The time response of the first-order system shown in Fig. 2-1 can be plotted using equations (9). The contents of Table 2-2 can be easily formatted into a spreadsheet program as shown here in Table 4-1.

Table 4-1. Spreadsheet formulas for 1st order simulation.

Column	A	B	C	D
Row				
1	DELTAT=	0.02		
2	TC1=	1.00		
3	GAIN=	1.00		
4				
5	X-AXIS	1ST		2ND
6	SERIES	SERIES		SERIES
7	=====	=====	=====	=====
8	t	x	x1	y
9	=====	=====	=====	=====
10	0	0	0	0
11	A10+\$B\$1	1 (\$B\$3*B11-D10)/\$B\$2	D10+(C10+C11)*\$B\$1/2	
12	A11+\$B\$1	1 (\$B\$3*B12-D11)/\$B\$2	D11+(C11+C12)*\$B\$1/2	
13	A12+\$B\$1	1 (\$B\$3*B13-D12)/\$B\$2	D12+(C12+C13)*\$B\$1/2	

It is important to restate that all of the information in Table 4-1 will not be displayed on the screen, that is, the formulas shown in rows 11 through 13 will not be shown. The text information contained in cells A1..A3 correspond to the constants  $\Delta t$ ,  $\tau_1$ , and  $A_0$ , respectively. The values for these constants are entered by the user into cells B1...B3. Also notice that text and horizontal bars (=) were added in rows 5 through 9 in order to make the spreadsheet more organized and readable.

The initial values are entered by the user in row 10. In this example, the input  $x(t)$  is a simple unit-step function and the values "1" are entered under column B by the user. Once the spreadsheet is setup, only those parameters mentioned above need be entered by the user. That is, the formulas should be protected from change.

The formula for time in cell A11 takes the old time at cell A10 and adds the constant  $\Delta t$  to it. The dollar sign (\$) used in formulas indicate that a cell's coordinate(s) is absolute. This feature allows for the copying of formulas while keeping certain addresses unchanged during the copying process. Notice that when the formula in cell A11 was copied to cells A12...A13 that the address \$B\$1 remained unchanged. This is necessary because its contents is  $\Delta t$  which is fixed at the value entered in cell B1. Note that the "\$" can be specified in front of the

column letter, in front of the row number or both, as used here in this example.

The actual (partial) spreadsheet for this first-order example is shown in Table 4-2. Again, notice that the formulas are not displayed nor printed, but the data cells show the results of the calculations. The column widths here are set to "9". It should be noted here that the widths of the columns shown in the previous Table (Table 4-1) were expanded for the purpose of showing the formulas in the corresponding cell locations.

Table 4-2. Spreadsheet (partial) for 1st order simulation.

Column	A	B	C	D
Row				
1	DELTAT=	0.02		
2	TC1=	1.00		
3	GAIN=	1.00		
4				
5	X-AXIS	1ST		2ND
6	SERIES	SERIES		SERIES
7	=====	=====	=====	=====
8	t	x	x1	y
9	=====	=====	=====	=====
10	0	0	0	0
11	0.02	1	1.00	0.01
12	0.04	1	0.99	0.03
13	0.06	1	0.97	0.05

The graph for this first-order example is shown in Fig. 4-1. The spreadsheet was expanded by adding additional rows (by coping row 13) in order to calculate the time response out to 4 seconds as shown in the graph. For this simulation, the system input was a unit-step with the system time-constant and gain normalized to unity. Now that the spreadsheet is "programmed", these parameters can be changed by moving the cursor to the desired cell and entering a new value. Again, by depressing the "F10" key, the new plotted graph will be displayed on the screen. Once the formulas in the spreadsheet are finalized ("debugged", tested and validated), those cells should be protected to prevent accidental erasure or corruption by an operator mistake.

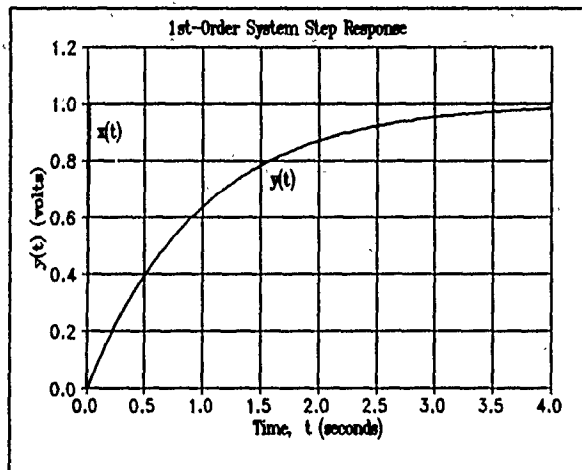


Figure 4-1. Step response of 1st order system.

#### 4.2 Second-order system simulation

The time response of the damped second-order system shown in Fig. 2-3 can be plotted using equations (11). The contents of Table 2-3 can be formatted into a spreadsheet program as shown in Table 4-3.

Table 4-3. Spreadsheet formulas for 2nd order simulation.

Column	A	B	C	D	E	F
Row						
1	DELTAT=	0.05				
2			TC=	1.00	TC=	1.00
3			GAIN=	1.00	GAIN=	1.00
4						
5	X-AXIS	1ST		2ND		3RD
6	SERIES	SERIES		SERIES		SERIES
7						
8	t	x	xi1	y1	xi2	y2
9						
10	0	0	0	0	0	0
11	A10+\$B\$1	1	(D\$3*B11-D10)/D\$2	D10+(C10+C11)*\$B\$1/2	(F\$3*D11-F10)/F\$2	F10+(E10+E11)*\$B\$1/2
12	A11+\$B\$1	1	(D\$3*B12-D11)/D\$2	D11+(C11+C12)*\$B\$1/2	(F\$3*D12-F11)/F\$2	F11+(E11+E12)*\$B\$1/2
13	A12+\$B\$1	1	(D\$3*B13-D12)/D\$2	D12+(C12+C13)*\$B\$1/2	(F\$3*D13-F12)/F\$2	F12+(E12+E13)*\$B\$1/2

Table 4-1 was modified and then used to create Table 4-3. First, The data in rows 2 and 3 were moved from columns A and B to columns C and D, respectively. This causes all of the information concerning the first 1st order section to be situated under columns C and D. The spreadsheet program will automatically update all formulas that use these cells. That is, it will change the formulas to show the new cell addresses when the cells are moved. Therefore, \$B\$2 and \$B\$3 are automatically changed to \$D\$2 and \$D\$3, respectively. Hence, the formula in cell C11 of Table 4-1 is changed from

$$(\$B\$3*B11-D10)/\$B\$2 \text{ to } (\$D\$3*B11-D10)/\$D\$2$$

Since the formula in cell D11 does not use cells B2 nor B3, it is unaffected by this move operation. If the "\$" preceding the "D" in \$D\$2 and \$D\$3 in cell C11 is now manually erased, the formula becomes

$$(D\$3*B11-D10)/D\$2$$

as shown in cell C11 in Table 4-3. The "\$" was erased to allow copying the formulas in cells C11 and D11 to cells E11 and F11 as illustrated in the table. Therefore, all cell address letters in the formulas that do not have the "\$" prefix are incremented by 2, that is B's, C's and D's become D's, E's and F's, respectively. Note that the cell address row numbers are unaffected because the copying source and destination locations are in the same row.

Table 4-4. Spreadsheet (partial) for 2nd order simulation.

Column	A	B	C	D	E	F
Row						
1	DELTAT=	0.05				
2			TC=	1.00	TC=	1.00
3			GAIN=	1.00	GAIN=	1.00
4						
5	X-AXIS	1ST		2ND		3RD
6	SERIES	SERIES		SERIES		SERIES
7	=====	=====	=====	=====	=====	=====
8	t	x	xi1	y1	xi2	y2
9	=====	=====	=====	=====	=====	=====
10	0	0	0	0	0	0
11	0.05	1	0.98	0.03	0.03	0.00
12	0.10	1	0.93	0.07	0.07	0.00
13	0.15	1	0.88	0.12	0.12	0.01

The formulas shown in cells C11 and D11 are now optimum. They can be copied downward to provide for additional rows or they can be copied across as described here to provide for higher-order systems. In practice, formulas C11

and D11 are entered into the spreadsheet first. Then, row 11 is then copied downward to provide for the required additional rows. Next, the entire columns C and D can be copied to columns E and F, respectively.

The actual (partial) spreadsheet for this second-order example is shown in Table 4-4. Note that  $\Delta t$  was increased to 0.05 seconds. This was done to extend the plotting time out to 6 seconds as seen in Fig. 4-2.

For this simulation, the input is also a unit-step with both sections having unity gain and time-constants. Note that both  $y_1(t)$  and  $y_2(t)$  are plotted in the graph shown in Fig. 4-2.

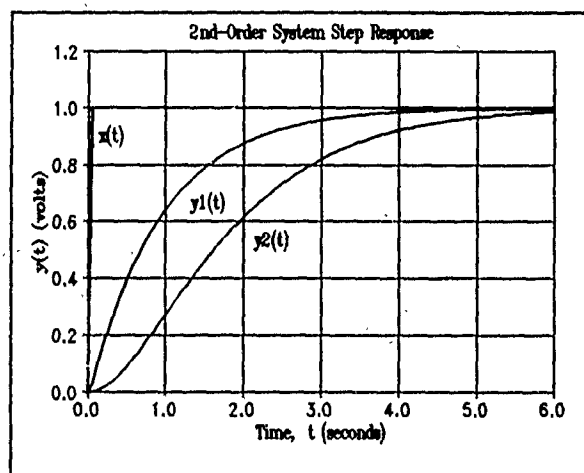


Figure 4-2. Step response of 2nd order system.

Since there is no feedback from the final output  $y_2(t)$  back into the system, the time response of the first section  $y_1(t)$  is totally independent from that of the second section. Hence, this spreadsheet can be used to simulate both 1st and 2nd-order systems and the previous spreadsheet shown in Table 4-2 is no longer needed. One major disadvantage of this is that this spreadsheet will take longer to calculate than the previous one. This problem can be eliminated by erasing the cell formulas below cells E11 and F11. These two cells can always be recopied downward as needed.



#### 4.3 Second-order system with feedback simulation

A block diagram of a damped second-order system with feedback is shown in Fig. 4-3. Notice that the output of the system  $Y_2(s)$  is fed back via the feedback network  $H(s)$ , and that the input to the first section is no longer  $X(s)$ , but is the difference (system error)  $X_e(s) = X(s) - H(s)Y_2(s)$ .

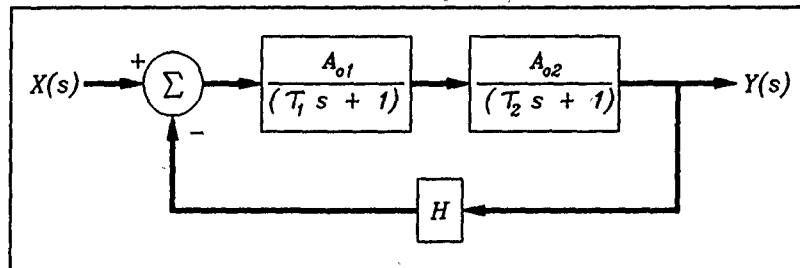


Figure 4-3. Second-order system with feedback.

The spreadsheet in Table 4-4 can be easily modified to accommodate feedback from the output. In this spreadsheet, the formulas for x11 in column C are "looking" at the data in the cells of column B. If a new column is inserted (added) between the existing columns A and B, the spreadsheet will automatically update all formulas, that is, all cell column addresses are incremented by one, and the operation of the spreadsheet remains the same including graphing. The text "x" now in cell C8 should be edited to "x1" because all of the data in this column (C) is the input to the first section. The new cells C1 ( $\Delta t$ ), C5 ("1ST") and C6 ("SERIES") should be moved back to their original locations (column B).

Table 4-5. Spreadsheet (partial) for 2nd order system with feedback.

Column	A	B	C	D	E	F	G
Row							
1	DELTAT=	0.05					
2	H=	1.00		TC=	1.00	TC=	1.00
3				GAIN=	1.00	GAIN=	1.00
4							
5	X-AXIS	1ST			2ND		3RD
6	SERIES	SERIES			SERIES		SERIES
7	=====	=====	=====	=====	=====	=====	=====
8	t	x	x1	x11	y1	x12	y2
9	=====	=====	=====	=====	=====	=====	=====
10	0	0	0	0	0	0	0
11	0.05	1	1.00	1.00	0.03	0.03	0.00
12	0.10	1	1.00	0.97	0.07	0.07	0.00
13	0.15	1	1.00	0.92	0.12	0.12	0.01

The actual (partial) spreadsheet for this system is shown in Table 4-5. Notice that the feedback factor is assumed to be a constant and its value is located in cell B2. The values for the system input  $x$  are in column B as in previous spreadsheets. The formula for the output of the subtractor (input to the first section) in cell C11 becomes  $B11 - \$B\$2 * G10$ , where B11 is the current input  $x(t)$ ,  $\$B\$2$  is the feedback factor  $H$  and G10 is the previous output  $y_2(t)$ . As done previously, this formula is copied from cell C11 downward to the required number of rows.

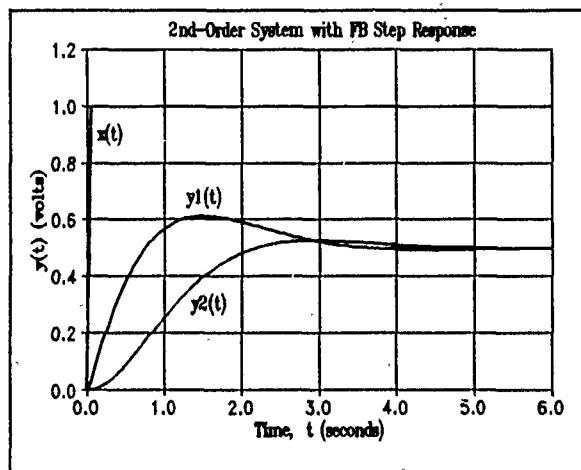


Figure 4-4. Step response of system with feedback.

For this simulation, the feedback factor was set to unity. Therefore, as expected, the steady-state value of the output  $y_2(t)$  is one-half of the unity input. This is a special case because the gains  $A_{o1}$  and  $A_{o2}$  are unity as well so that the steady-state loop gain is one. Also note that if the feedback factor  $H$  is set to zero, the time response is the same as that for the previous system, and it can be used to simulate first-order systems.

The feedback factor need not be restricted to a constant. For example, the feedback could be a first-order lag (first-order transfer function). Hence, this lag would be added into the spreadsheet by adding two additional columns as would be done for a third-order system. The output  $y_3(t)$  would then be fed back rather than  $y_2(t)$  as was done in the system spreadsheet in Table 4-5.

#### 4.4 Second-order system with proportional controller

In a process control system, a system controller is used to drive the system to obtain a desired output value. In general, the controller samples the process output  $Y$ , compares its value with that of the desired output value  $X$  (reference input to the controller) and produces an output  $X_1$  that drives the system such

that the system error is minimized.

The functional block diagram for a simple process control system having a proportional controller is shown in Fig. 4-5. This diagram is very similar to that shown in Fig. 4-3, except that a proportional gain block was added between the output from the subtractor and the input to the system.

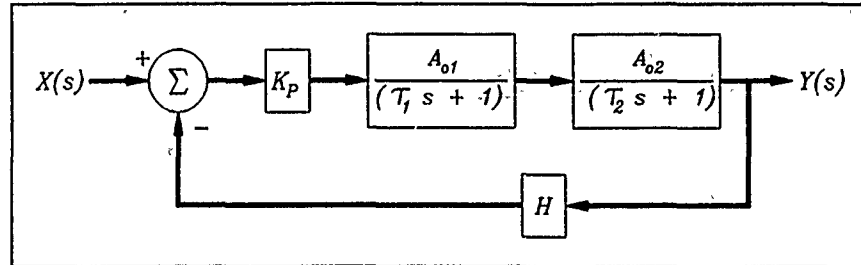


Figure 4-5. System with proportional controller.

The output from the subtractor is the system error given by  $X_e(s) = X(s) - H(s)Y_2(s)$ , where  $Y_2(s)$  is the output of the system  $Y(s)$ . The input to the process plant or system being controlled is  $X_1(s) = K_p X_e(s)$ .

Table 4-6. Spreadsheet (partial) for system with proportional control.

Column	A	B	C	D	E	F	G
Row							
1	DELTAT=	0.05					
2	H=	1.00		TC=	1.00	TC=	1.00
3	KP=	5.00		GAIN=	1.00	GAIN=	1.00
4							
5	X-AXIS	1ST			2ND		3RD
6	SERIES	SERIES			SERIES		SERIES
7	=====	=====	=====	=====	=====	=====	=====
8	t	x	x1	x11	y1	x12	y2
9	=====	=====	=====	=====	=====	=====	=====
10	0	0	0	0	0	0	0
11	0.05	1	5.00	5.00	0.13	0.13	0.00
12	0.10	1	4.98	4.86	0.37	0.37	0.02
13	0.15	1	4.92	4.55	0.61	0.59	0.04

The simulation spreadsheet for this system is very similar to that given in Table 4-5 as shown here in Table 4-6. Note that the value of the proportional gain  $K_p$  is located in cell B3 and that the formula for x1 in cell C11 was changed from  $B11-\$B\$2*G10$  to  $(B11-\$B\$2*G10)*\$B\$3$ .

The graph for this system with  $K_p=5$  is shown in Fig. 4-6. Notice that this system is slightly under-damped (10% overshoot) and since  $K_p$  is only 5, the steady-state error is approximately 20%.

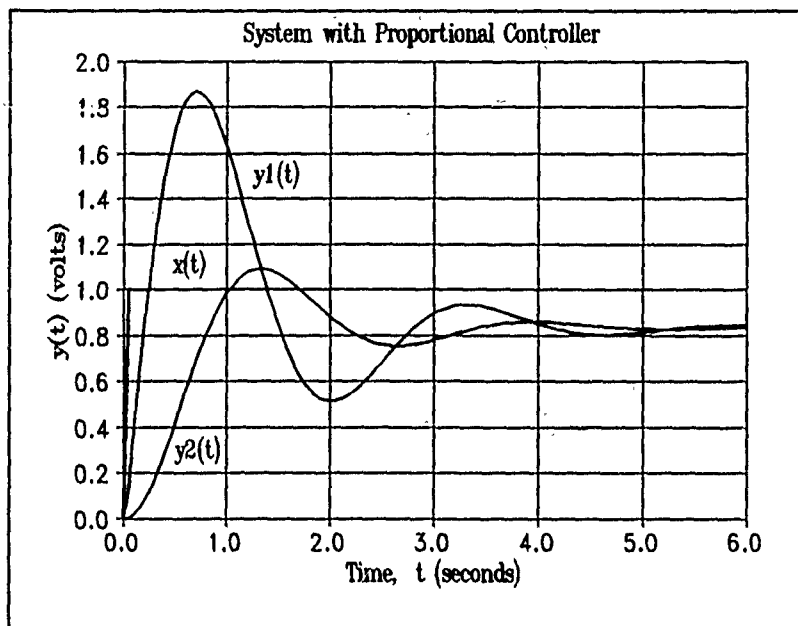


Figure 4-6. Step response with proportional controller.

#### 4.5 Second-order system with proportional and integral controller

The functional block diagram for a process control system having a proportional and integral controller is shown in Fig. 4-7. The integrator in the controller is used to reduce steady-state errors while providing for good dynamic response. In the previous controller that had only proportional control, the steady-state error was significant (20% for  $K_p=5$ ). Increasing the proportional gain would help reduce this error to some extent, but would cause severe overshoot and the system could become marginally stable. The integral gain  $K_I$  is the inverse of the integrator's time-constant so that as  $K_I$  is increased, the time-constant decreases and the integrator responds faster. An ideal integrator has a steady-state gain of infinity, hence the system error becomes zero for steady-state.

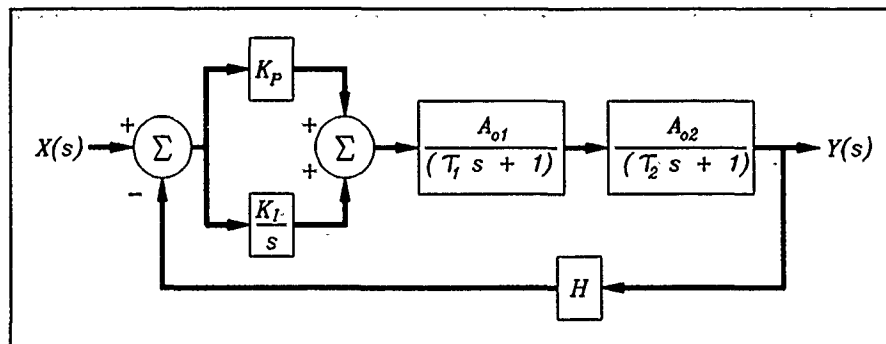


Figure 4-7. System with proportional and integral controller.

The spreadsheet for this system is shown in Table 4-7. Two new columns were added to Table 4-6:  $x_e$  and  $y_I$ , where  $x_e$  is the error signal from the subtractor and  $y_I$  is the output from the integrator, respectively. The formulas for  $x_e$  and  $y_I$  in row 11 are given as follows:  $C11=B11-\$B\$2*I10$  and  $D11=D10+(C10+C11)*\$B\$1/2$ , respectively. The input to the system  $X_1=K_p X_e+Y_I$  or for row 11,  $E11=\$B\$3*C11+D11$ .

Table 4-7. Spreadsheet (partial) for system with PI controller.

Column	A	B	C	D	E	F	G	H	I
Row									
1	DELTA=	0.05							
2	H=	1.00				TC=	1.00	TC=	1.00
3	KP=	5.00				GAIN=	1.00	GAIN=	1.00
4	KI=	1.00							
5	X-AXIS	1ST					2ND		3RD
6	SERIES	SERIES					SERIES		SERIES
7	=====	=====	=====	=====	=====	=====	=====	=====	=====
8	t	x	$x_e$	$y_I$	$x_1$	$x_{11}$	$y_1$	$x_{12}$	$y_2$
9	=====	=====	=====	=====	=====	=====	=====	=====	=====
10	0	0	0	0	0	0	0	0	0
11	0.05	1	1.00	0.03	5.03	5.03	0.13	0.13	0.00
12	0.10	1	1.00	0.07	5.06	4.93	0.37	0.37	0.02
13	0.15	1	0.98	0.12	5.05	4.67	0.61	0.60	0.04

The unit-step response for this system is shown in Fig. 4-8. The value of the proportional gain  $K_p$  was kept at 5 and the integral gain  $K_I$  was set to unity. Note that the steady-state error is zero, that is,  $y_2(t)$  approaches the steady-state value of unity for a unit-step input to the controller.

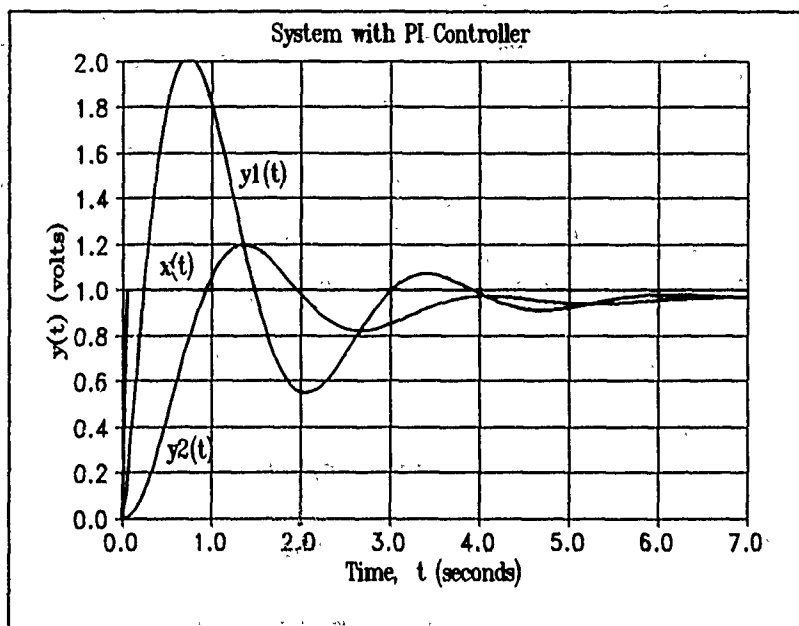


Figure 4-8. Unit-step response of system with PI controller.

#### 4.6 Large-signal response of real systems

In real systems, the range over which a signal can operate is usually limited by some mechanical or electrical constraints. For example, the output signal range for a typical operational amplifier is limited to approximately  $\pm 13$  volts when using standard  $\pm 15$  VDC power supplies. That is, the linear range of operation is restricted to  $\pm 13$  volts and the output becomes saturated or limited to this values when attempting to exceed these limits. Operational amplifiers are often used in proportional and PI controllers, hence, the operating signal range must be considered when developing models for these controllers. Likewise, all mechanical systems and mechanical actuators have mechanical limits which can not be exceeded.

The simulation spreadsheet shown in Table 4-6 uses a proportional gain  $K_p = 5$ . Hence, the output of the controller  $X_1$  transitions up to +5 volts for a unit-step (+1 volt) input as seen in cell C11. If the input step value is increased to 10 volts, the amplifier will saturate and remain saturated until the error becomes less than  $13/5$  or 2.6 volts, that is, until the output reaches +7.4 volts. During this time of saturation, the input to the system being controlled  $X_1$  is constant at +13 volts and does not decrease as indicated in column C of the table. Therefore, the actual large-signal step response will differ significantly from that shown in the graph of Fig. 4-6.

To perform signal limiting in a spreadsheet involves the use of logic formulas. That is, the signal value is compared with the established limits and a logical decision is made to determine the calculated value of the cell. The logical If...Then statement can be used to make the required comparison and determine the value of the cell.

As shown in Table 4-8, a column was added into Table 4-6 to provide spreadsheet "space" for the additional information: LIM1H and LIM1L. The new column is designated x1LIM which is the limited values for the column x1. The values for LIM1H and LIM1L are located in cells D2 and D3, respectively. The formulas for x11 (column E) now "look" for data from x1LIM in column D rather than x1 in column C. The logic formula in cell D11 is as follows:

D11=IF(C11>=\$D\$3#AND#C11<=\$D\$2,C11,IF(C11>\$D\$2,\$D\$2,\$D\$3))

This formula first checks to determine if cell C11 is between LIM1L and LIM1H (D3 and D2, respectively), that is, if C11 is greater than or equal to LIM1L and C11 is less than or equal to LIM1H. If this is true, then D11 is set to C11. If this is not true, C11 must be greater than LIM1H or less than (more negative than) LIM1L. Therefore, if C11 is greater than LIM1H, then D11 is set to this upper limit. If it is not, then C11 must be less than LIM1L, so D11 is set to this value.

Table 4-8. Spreadsheet with proportional control limiter

Column	A	B	C	D	E	F	G	H
Row								
1	DELTAT=	0.05						
2	H=	1.00	LIM1H=	+13.00	TC=	1.00	TC=	1.00
3	KP=	5.00	LIM1L=	-13.00	GAIN=	1.00	GAIN=	1.00
4								
5	X-AXIS	1ST		4TH		2ND		3RD
6	SERIES	SERIES		SERIES		SERIES		SERIES
7	=====	=====	=====	=====	=====	=====	=====	=====
8	t	x	x1	x1LIM	x11	y1	x12	y2
9	=====	=====	=====	=====	=====	=====	=====	=====
10	0	0	0	0	0	0	0	0
11	0.05	10	50.00	13.00	13.00	0.33	0.33	0.01
12	0.10	10	49.86	13.00	12.68	0.87	0.86	0.04
13	0.15	10	49.80	13.00	12.03	1.58	1.54	0.10

The system input for the simulation in the spreadsheet shown in Table 4-8 is a 10V step. If there were no limits to consider, the response would be ten times the unit-step response of the system simulated in Table 4-6 and shown in the graph in Fig. 4-6. For the time response plot shown in Fig. 4-9, the input to the system being controlled x1LIM is constant at LIM1H (+13V) for about two seconds. During this time, there is essentially no feedback from the system output so the system behaves like it is open-loop responding to a step-input of + 13 volts. Also notice that the output does not overshoot the 10V input, but does overshoot the final value (approximately 8 volts). Hence, the limiter does not affect the damping or stability of the system, but only the large-signal dynamic

response. If the step was reduced to a unit step, the time response would be identical to that of the previous system because the limiter will have no affect on limiting the input signal to the system being controlled.

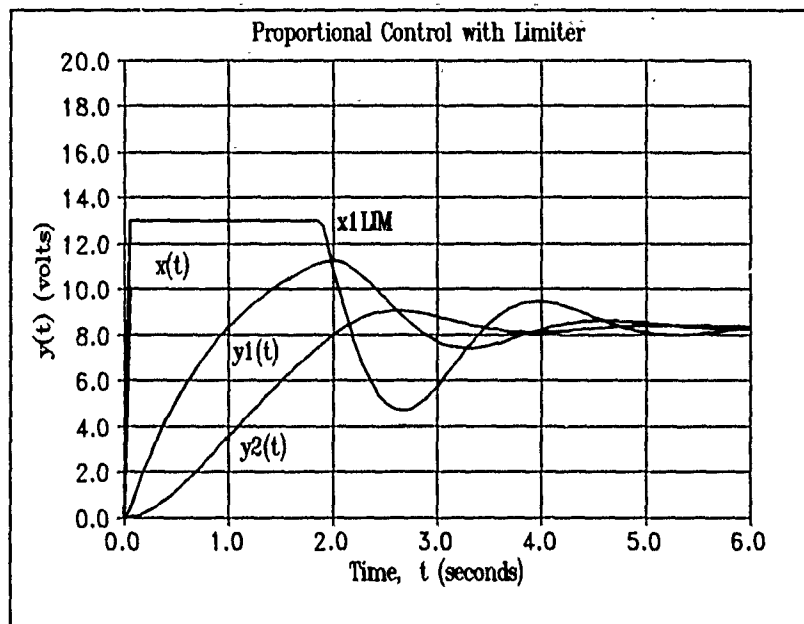


Figure 4-9. 10V step response - proportional control with limiter.

To prevent integrator windup during large-signal transient conditions, a limiter is often incorporated into the integrator design in a proportional plus integral controller. Basically, it is useless and undesirable to have the integrator attempt to minimize the systems steady-state error until the system approaches this final value. If not limited, the integrator will accumulate (integrate) the large-signal errors and actually cause the controller to overshoot the desired steady-state controller output value.

Many controllers also limit the error signal (from the subtractor) before it is fed to the proportional and integrator elements as illustrated in Table 4-9. The time response of this system with a 10V step input is shown in the graph in Fig. 4-10. Notice that the output from the integrator  $y_I$  is initially ramping at the rate 2 volts/second ( $LIMH=2$  and  $K_I=1$ ) while the error signal is limited, that is, for approximately the first 2.5 seconds.



Table 4-9. PI controller with error limiter.

Column	A	B	C	D	E	F	G	H	I	J
Row										
1	DELTA=	0.05								
2	H=	1.00	LIMEH=	2.00			TC=	1.00	TC=	1.00
3	KP=	5.00	LIMEL=	-2.00			GAIN=	1.00	GAIN=	1.00
4	KI=	1.00								
5	X-AXIS	1ST			4TH			2ND		3RD
6	SERIES	SERIES			SERIES			SERIES		SERIES
7	=====	=====	=====	=====	=====	=====	=====	=====	=====	=====
8	t	x	xe	xeLIM	yI	x1	x11	y1	x12	y2
9	=====	=====	=====	=====	=====	=====	=====	=====	=====	=====
10	0	0	0	0	0	0	0	0	0	0
11	0.05	10	10.00	2.00	0.05	10.05	10.05	0.25	0.25	0.01
12	0.10	10	9.99	2.00	0.15	10.15	9.90	0.75	0.74	0.03
13	0.15	10	9.97	2.00	0.25	10.25	9.50	1.23	1.20	0.08

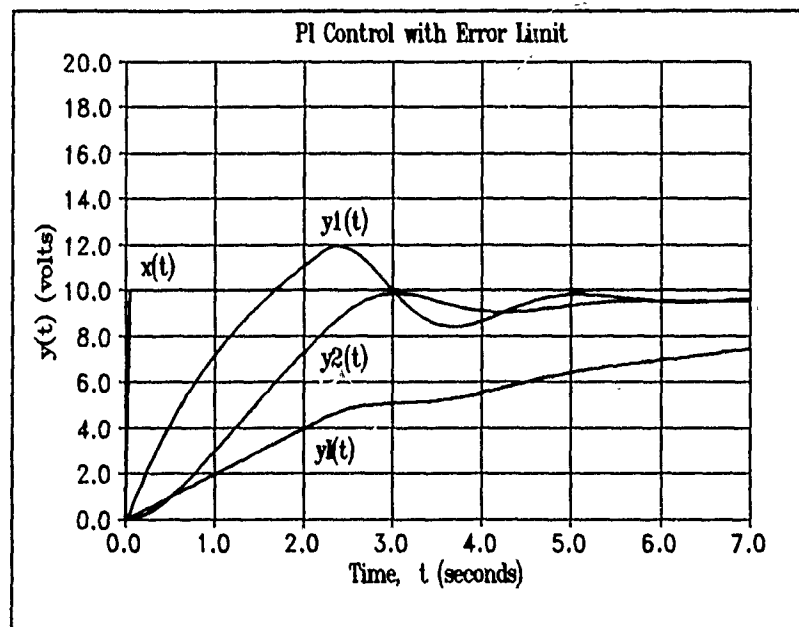


Figure 4-10. 10V step response - PI control with error limiter.

Often, the combined outputs from the controller (proportional plus integral outputs) are limited either intentionally or by the mechanical limits of the system actuator. These limiters can also be incorporated into the simulation spreadsheet using the same method as in the previous example.

#### 4.7 Simulation of nonlinear systems

Spreadsheet formulas can be used to produce practically any nonlinear function required to simulate the nonlinear characteristics of a process plant. A nonlinear scaling element can be inserted or cascaded in line with the linear sections to provide for the desired model.

As an example, suppose that the system being controlled has the nonlinear characteristics as illustrated by the function shown in Fig. 4-11. In this example, the output  $y(x)$  is a nonlinear function of the input  $x$  and is given by:  
 $y = x + 0.1x^2$ .

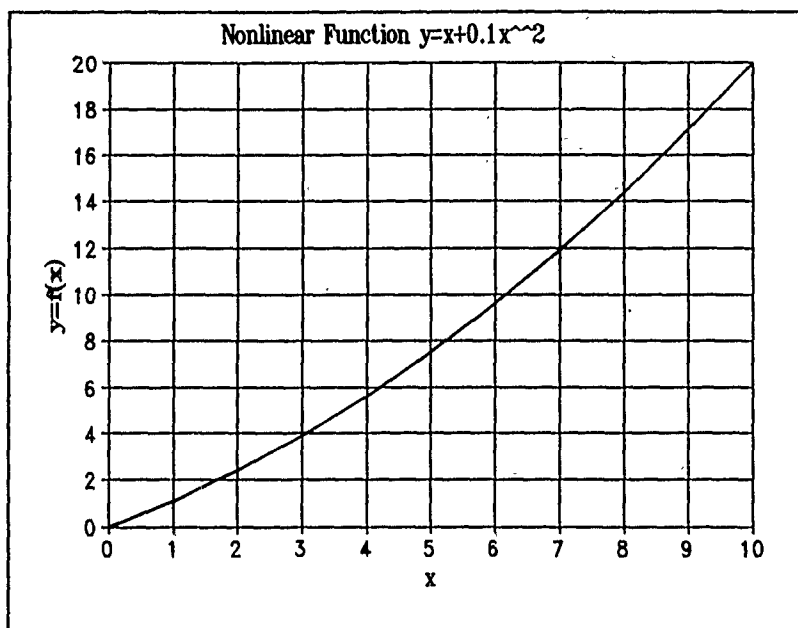


Figure 4-11. Example of nonlinear system.

If this nonlinear function block is inserted (cascaded) after the output of the second 1st-order section  $y_2$  of the system shown in Fig. 4-7, the new output of the system becomes  $y_3 = y_2 + 0.1y_2^2$ . This new output  $y_3$  is now fed back to the subtractor in the PI controller instead of  $y_2$ .

The spreadsheet shown in Table 4-7 can be modified by adding a new column  $y_3$  after the  $y_2$  column as shown in Table 4-10. The formula for  $y_3$  in cell J11 is given by  $I11+0.1*I11^2$ , where " $^2$ " denotes "to the power of". The formula for  $x_e$  in cell G11 must now be changed to  $B11-\$B\$2*J10$ . No other actions are necessary except that the formulas in row 11 must be copied downward as required.

Table 4-10. Spreadsheet for nonlinear system - step input: 0 to 1.

Column	A	B	C	D	E	F	G	H	I	J
Row										
1	DELTA T=	0.05								
2	H=	1.00				TC=	1.00	TC=	1.00	
3	KP=	5.00				GAIN=	1.00	GAIN=	1.00	
4	KI=	1.00								
5	X-AXIS	1ST								
6	SERIES	SERIES					2ND		3RD	4TH
7							SERIES		SERIES	SERIES
8	t	x	x0	y1	x1	x11	y1	x12	y2	y3
9										
10	0	0	0	0	0	0	0	0	0	0
11	0.05	1	1.00	0.03	5.03	5.03	0.13	0.13	0.00	0.00
12	0.10	1	1.00	0.07	5.06	4.93	0.37	0.37	0.02	0.02
13	0.15	1	0.98	0.12	5.05	4.87	0.61	0.60	0.04	0.04

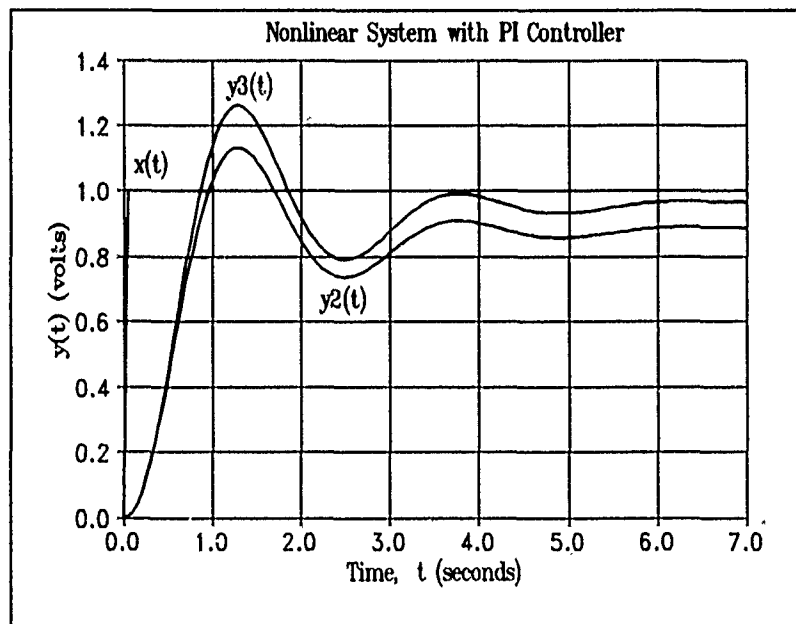


Figure 4-12. Unit-step response (0 to 1V) of nonlinear system.

Notice that the input is a simple unit-step starting at 0. Hence, the initial conditions in row 10 are all zero. The time response for this system is shown in Fig. 4-12. It is similar to the step response graph shown in Fig. 4-8, except that  $y_3$  is the output (not  $y_2$ ) and the overshoot increased slightly from 20 to 25%.

The table and graph for the same system with an unit-step input starting at 9 instead of 0 are shown in Table 4-11 and Fig. 4-13, respectively. It is very important to note here that all of the initial conditions are not zero. At time  $t=0$ , the system is in a steady-state condition with a constant input  $x=9$ . Therefore,  $x_e$ ,  $x_{i1}$  and  $x_{i2}$  are zero; and  $y_3=9$  because the integrator in the controller forces the steady-state position error to zero.

Table 4-11. Spreadsheet for nonlinear system - step input: 9 to 10.

Column	A	B	C	D	E	F	G	H	I	J
Row										
1	DELTA T=	0.05								
2	H=	1.00				TC=	1.00	TC=	1.00	
3	KP=	5.00				GAIN=	1.00	GAIN=	1.00	
4	KI=	1.00								
5	X-AXIS	1ST					2ND		3RD	4TH
6	SERIES	SERIES					SERIES		SERIES	SERIES
7	=====	=====	=====	=====	=====	=====	=====	=====	=====	=====
8	t	x	$x_e$	$y_I$	$x_{i1}$	$y_1$	$x_{i2}$	$y_2$	$y_3$	
9	=====	=====	=====	=====	=====	=====	=====	=====	=====	=====
10	0	9	0	5.72	5.72	0	5.72	0	5.72	9
11	0.05	10	1.00	5.75	10.75	5.03	5.85	0.13	5.73	9.01
12	0.10	10	0.99	5.80	10.76	4.92	6.10	0.37	5.74	9.03
13	0.15	10	0.97	5.85	10.68	4.58	6.34	0.60	5.76	9.09

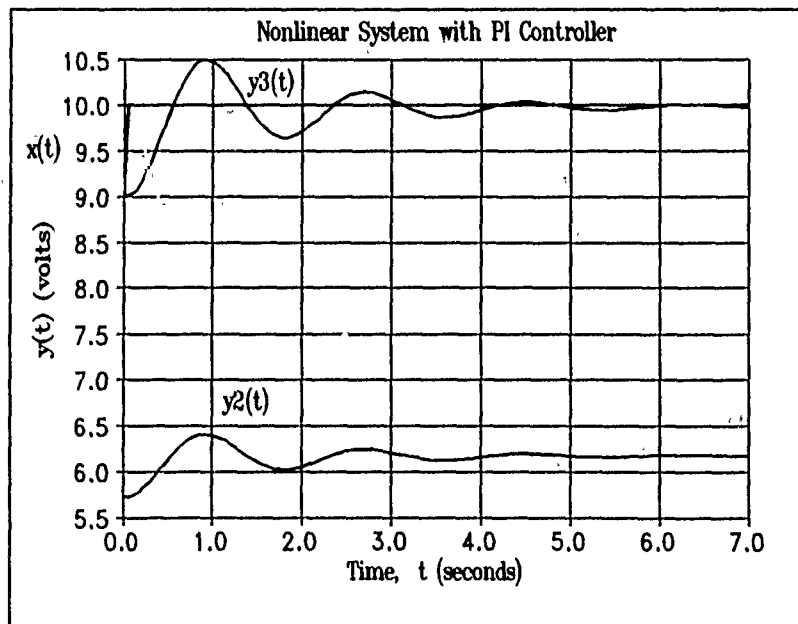


Figure 4-13. Unit-step response (9 to 10V) of nonlinear system.

The initial condition for  $y_2$  is the steady-state value that gives  $y_3=9$ . In general, this value can be determined by applying the quadratic formula to the equation:  $x^2 + 10x - 10y = 0$ . For this case  $y_3=y=9$ , hence  $y_2=x=5.724$ . A formula could be used to calculate  $y_2$  in cell I10 for any initial value of  $y_3$ . The formula for cell I10 is given by:  $\text{SQRT}(100+40*J10)/2-5$ .

The initial values for  $y_1$  in cell G10 and  $x_1$  in cell E10 can be calculated using the following formulas: I10/I3 and G10/G3, respectively. The formula for the initial value for  $y_1$  in cell D10 is simply +E10. The reason for this is that the integrator is driving the system error to zero. Therefore, the output from the proportional gain block is zero with zero system error. If these formulas are entered as directed, the initial conditions will automatically be calculated for any initial starting point by entering the initial condition of  $y_3$  into cell J10.

It is interesting to note here that the value of dynamic loop gain in a nonlinear system depends on the operating point. In this example, the dynamic gain of the nonlinear element increases from 1.18 to 2.15 as the output operating point is increased from 1 to 10, respectively. This will affect the dynamic time response as can be seen by comparing the two graphs. Note the overshoot increased from 25% to 50% as the starting point for the unit step input was increased from 0 to 9.

## 5. CONCLUSIONS AND FINAL COMMENTS

Spreadsheet programs running on today's high-performance personal computers are very powerful computer aided design tools including the simulation of analog systems as presented here. Some engineers and scientists still have reservations concerning using spreadsheet programs to perform analytical tasks because they believe that these software packages are only used by business personnel for financial purposes and that these programs are too limited to perform their required analysis. The author however has applied spreadsheet programs in many engineering applications, most recently, for the simulation of the new propulsion control system for the U.S. Coast Guard cutters *Polar Star* and *Polar Sea*. Other interesting applications include the design for a custom aspheric condensing lens used in a laser seeker for an airframe, canard control system simulation, active filter design, control system frequency response analysis including PI controller tuning and many other practical applications.

The traditional approach of writing analytical programs in languages such as FORTRAN and BASIC will continue to dominate over the use of spreadsheet programs. However, spreadsheets can be "programmed" very quickly because most of the "hard work" such as input/output data formats, control statements, display layout and printing and plotting routines are performed by the program. Therefore, the engineer only need be concerned with the modeling equations for the application.

## 6. REFERENCES

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## PERFORMANCE ASSESSMENT USING REAL TIME SIMULATION

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### 0 ABSTRACT

As part of the procurement of the Single Role Minehunter a performance assessment of the ship's position keeping and propulsion control system has been carried out. The assessment used duplicates of the control consoles destined for shipboard use. These consoles were interfaced to a real time simulation of the ship, its machinery and environment. A simplified simulation of the ship's data system formed an essential part of the simulation. The assessment was performed over a trials programme that included all aspects of operational requirements. This paper describes the steps involved in setting up this assessment in both management and technical aspects. The structure and facilities of the simulation system are described. The information gathered by the assessment programme is surveyed, together with comments on the value of the work.

### 1 INTRODUCTION

The use of real time simulation as a tool in the assessment of control and surveillance systems is not revolutionary. Its use in independent assessment, and the reasons for this method's acceptance are documented in reference (1).

The independent assessment of equipment procured by MoD in the past has been completed at MoD controlled establishments. Although subject to various management procedures the pressures to meet cost and programme targets were not governed by contract conditions.

The assessment of the Single Role Minehunter (SRMH) equipment was therefore a step into the unknown, in that the task was to be carried out by an independent contractor on MoD's behalf. The objective to be achieved did not change by going to a contractor. The MoD Project Group would, as a result of a successful assessment, be able to endorse the SRMH SMS and MCAS design. In addition, confidence would be gained in the systems' performance prior to integration and use in the ship.

An essential part of a successful assessment is well structured and thorough preparation. A clear and unambiguous objective must be defined and supported by definitions, and/or detailed assumptions of trials, standards and procedures.

In order to coordinate and to obtain input from all parties during the work programme, a Joint Trials Team (JTT) was established. Membership of the JTT included MoD interests as the procurement executive and users, the equipment contractor, and the assessment contractor. This body provided the forum through which the work was planned and reported.

## 2 PREPARATION

It is essential to prepare for a project thoroughly and in such a way to ensure success. The preparation started with a clear Statement of Requirements supported by a detailed response from a contractor. In their response the company was asked to provide a description of the procedures for:-

- project management
- quality control
- trial programme and content
- simulation model, structure and management
- system architecture

These statements then formed the basis for two documents:

- The Assessment Programme Management Specification
- The Requirements Specification for the SRMH Simulator

In the early days, the full nature of the assessment had been difficult to gauge. This could not be allowed to continue if costs and programme were to be maintained. The production of these two documents ensured that clear boundaries were defined for the work.

In order that progress could be maintained it was inevitable that assumptions would be made. These assumptions were recorded in some detail to ensure that their impact on the results could be judged. This approach also allowed some flexibility to be introduced into the programme. Many of the assumptions concerned operating limits. Provided that these were set at realistic levels, it was recognised that changes would be minimal if and when the correct information became available.

Considerable time and effort was put into the preparation of the Assessment Programme Management Specification, leading to full agreement from those involved. The document described all relevant issues and procedures including:

- Organisations interested in the Assessment Programme
- Trials
- Assumptions
- The Simulator, its design and validation
- Trials execution, its physical environment and operation
- Trials Programme
- Trials Documentation



The Requirement Specification for the SRMH Simulator described the design and procedures concerned with the simulator, addressing:

- User Description
- Functional Specification
- Constraints
- Life Cycle Aspects
- Installation Aspects
- Deliverables
- Acceptance Requirements
- Project Management
- Assumptions

Quality control procedures were introduced into the Project from day one, for both hardware and software. Quality audits, particularly concerned with software, provided confidence in the simulation software produced. Periodic checks by independent auditors provided further confirmation that adequate documentation and testing was being completed.

The benefits of this preparation became apparent as work on the simulator and trials documentation began with clear objectives and guidelines.

### 3 SIMULATOR SYSTEM

#### 3.1 Simulator Structure

The SRMH simulator consisted of the following major elements shown in block diagram form in Figure 1:

a) The 'user system' provided an interactive user interface for the control and monitoring of the simulation. In addition, it provided analysis and display facilities to deal with the data logged during the trials. The user interface made extensive use of 'windows' to allow different data to be displayed simultaneously. This is illustrated in Figure 2, where four windows have been set up. A cartridge tape drive was used for the transfer and archiving of data.

b) The 'real time system' housed the simulation model within a commercially available 68020-based single board microcomputer using the VME bus standard. All communication with the model was via the User System, or directly with the 'ship' via the I/O interface. The dynamic model of the SRMH was defined by the various sections of the SRMH Database detailing the primary machinery equipment dynamics, the ship dynamics and the environment.

The Ship Manoeuvring System (SMS) exchanges various items of command and navigation data with the Action Information Organisation (AIO) to issue propulsion demands. The AIO interfaces with the SMS via the Weapons System Data Bus (WSDB). Simulation of this interface contained only those functions relevant to the operation of either the SMS or the WSDB. This part of the model used a separate processor, with a serial data link to the rest of the real time system.

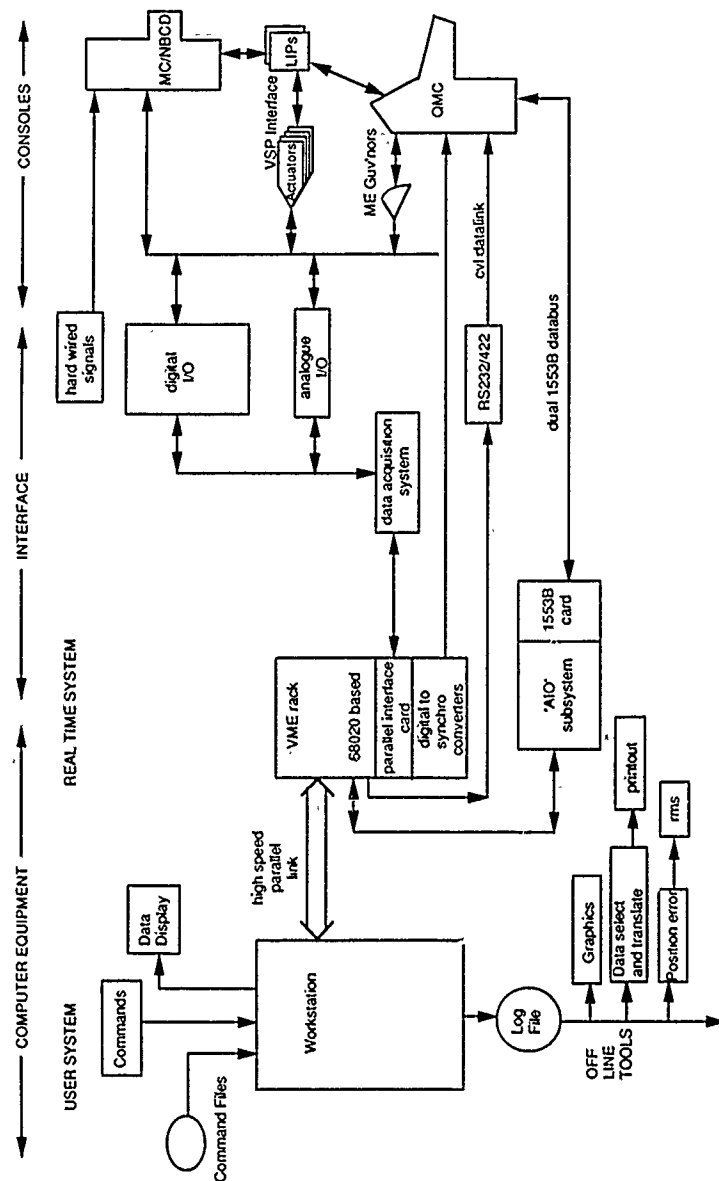


Figure 1: Block Diagram of SRMH Simulator

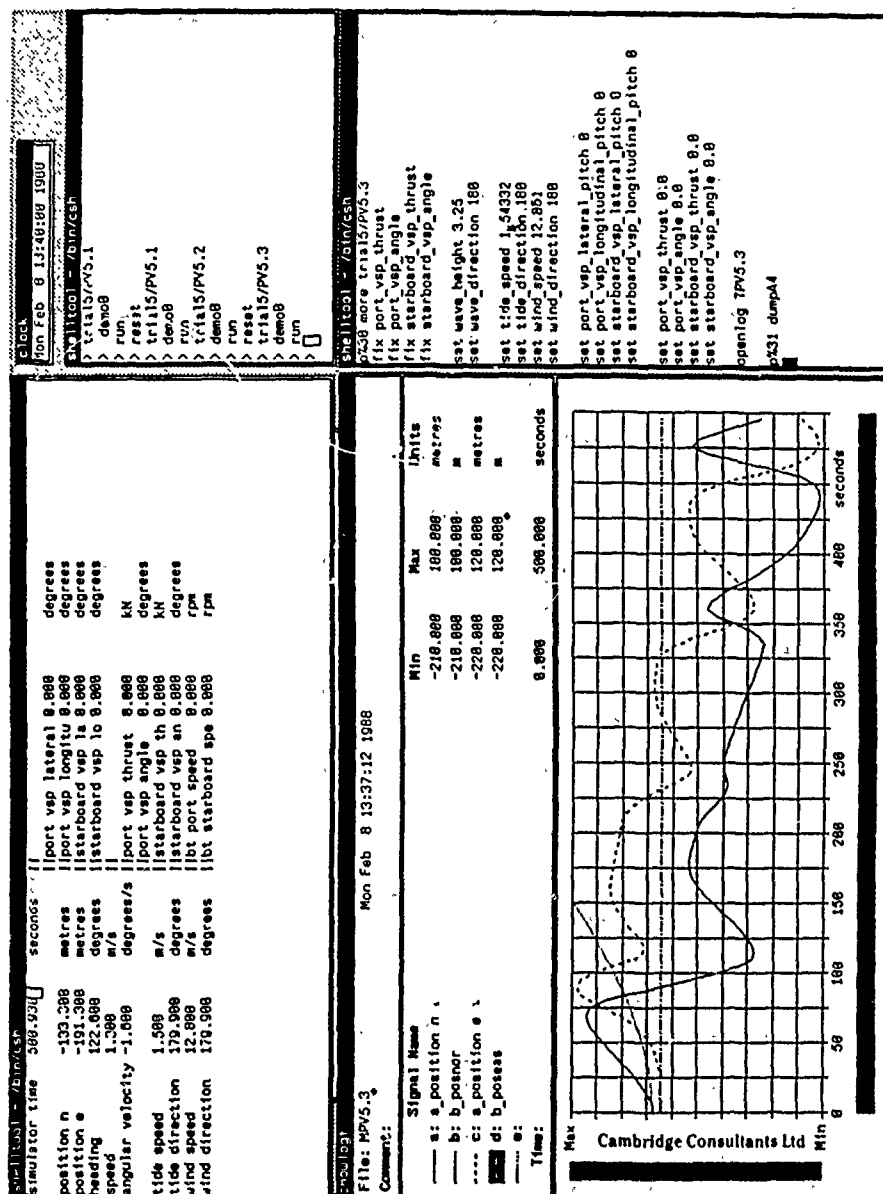


Figure 2: Example of User System Screen Display

- c) The I/O interface to the control consoles consisted of:
- i The WSDB interface was a MIL STD 1553B databus implemented using commercially available boards.
  - ii The recently installed correlation velocity log interfaces to the SMS using an RS422 serial data link. A commercially available RS232/RS422 communications converter was used for part of this interface.
  - iii Most analogue and digital signals pass from the consoles to the simulation software via appropriate signal conditioning circuits, and a proprietary data acquisition system. The channel count was small, with a total of around 20 analogues and 400 digitals for both input and output.
  - iv Several nav aids use synchro signals for transmission, and for these VME based digital to synchro converter boards were used.
  - v Some functions, notably the main engine governors were simulated in hardware using stepper motors. This was done to maximise compatibility with the equipment fitted to the SRMH, and to optimise simulator design.
  - vi Some status functions had no effect in the simulation, thus it was appropriate to simulate these functions in hardware using toggle switches, and potentiometers. These functions were not available for data logging and analysis by the User System.

### 3.2 User Interface

The user interface facilities can be divided into two sets. The software of the simulator itself provided facilities for the interactive control of the real time simulation; these are called the 'on-line' facilities. Other facilities were provided for the subsequent interpretation and analysis of the results data, and as such provided 'off-line' facilities.

#### a) On-line Facilities. The on-line facilities included:

- i interactive command facilities for the control and monitoring of the simulator, implemented through a 'window' referred to as the 'command vdu'; this is shown at the top right in the example shown in figure 2.
- ii facilities for the monitoring and display of simulator data, allowing up to 48 signals to be tabulated on the 'window' referred to as the 'signals vdu'; this is shown at the top left in the example shown in figure 2.
- iii a command file capability for executing a series of commands, typically, defining a set of initial conditions. the setting up of command scripts was performed (and tested) before execution time, thus minimising time pressures. an example of a command file is shown in the bottom right window in figure 2; in this case setting up values for certain simulator signals.
- iv commands acting within the simulation software were used to provide 'soft' causal links. this was preferred to encoding causality within the simulation code. this allowed functional links to be under the control of the user at all times. for example, interlock relationships were set up during

normal operations, and then removed when simulating fault or failure conditions.

v Selection and control of the data logged from the simulation for each run. Data samples could be either logged on change, or at a specified frequency.

b) Off-line Facilities. The off-line facilities consisted of a number of data processing tools that were specially written for this work. The design recognised that flexibility would be needed, and allowed some tools to be added during the analysis activity.

The raw data log files generated during each exercise were generally large. This resulted in the data processing tools running slowly for inspection and display purposes. Smaller files were more manageable and allowed execution at an acceptable speed. Thus pre-processing was performed to select a small number of important signals (such as ship position, heading and velocities), producing a smaller data file for routine use.

Processing of the results was generally intensive in its use of computing power, and hence could not operate while the simulator was running. Using Unix command files ("shell scripts") such processing was generally run overnight. Other Unix facilities such as 'grep' and 'sort' were also used to extract and sort data as part of this processing. The data processing tools are summarised below:

- \* a graphical display tool for screen and hard copy.
- \* a tool to select signals, and to translate the data samples into a text form from the binary log file.
- \* a reverse text to binary translator
- \* a tool to merge data from two binary log files.
- \* a tool to perform simple arithmetic operations on specified data samples.
- \* a tool to compute the ship's position error.
- \* a tool to compute the root mean square (rms) of the position error.

### 3.3 Simulation Model

There were several major parts to the simulation model:

i The dynamic model of the SRMH was defined by the various sections of the SRMH Database document [2]. Equations and tables given detail the ship dynamics for both hydrodynamic and aerodynamic interactions. The influence of the sonar's hydrodynamic drag, and that of the towed body (when deployed) is included. Using a simple Euler integration method, an interrupt driven calculation frequency of 10Hz was adequate.

ii Primary machinery dynamics are also defined by equations and tables in the SRMH Database document. For these faster dynamics, a calculation frequency of 100Hz was used.

iii Machinery state is determined by using a state machine reacting to the consoles' control signals. There was no interaction between 'associated' machinery (eg, lub oil pumps), or with sensors (eg, oil pressure, water temperature). This was a background processing task.

iv The ship's wind, wave and tide environment. This included the dynamic, non-steady components for gusting and high frequency wave effects. The dynamic environmental effects were specified in the form of complex power spectral density functions in the frequency domain. For the real time simulator, an equivalent time series was required, without undue loading of the processor. This target was achieved using a digital filtering algorithm, whose parameters varied according to conditions. This allowed the time series appropriate to the changing conditions to be generated.

v Simulation of navaid sensors was implemented to allow the simulated sensor values to be contaminated with noise.

vi The simplified simulation of the ship's AIO system and WSDB interface.

### 3.4 Verification and Validation

Before embarking on the trials programme, the simulation model needed to be verified and validated. In the absence of the 'real' SRMH, the following summarises the policy followed.

a) Verification of the Database Model. The major task was to verify the simulation against the contents of the SRMH Database document. To perform this verification, comparison with alternative sources of performance data was required:

i Feasibility work on the SRMH control system design used a simulation model based upon the SRMH Database (although an earlier edition). This model was written in Fortran, and implemented only the hull dynamics and a limited range of environmental conditions. After re-activating it and comparing results, many minor errors in both simulations had been identified and corrected. This work served to establish that the new simulation's performance had reached a level of maturity to allow meaningful comparison with other data from outside.

ii The suppliers of the SRMH control system have also developed a simulation model in support of their design and manufacturing programme. As part of their support activity, simulation work was carried out in order to provide wide ranging data for comparison. A series of test and short manoeuvres exercised the major parts of the simulation model representing the propulsion machinery and the hull dynamics using constant environmental conditions.

Both models agreed over a wide range of conditions. The qualitative agreement obtained gave confidence that both simulations were accurate representations of the SRMH Database. Comparison showed that:

- \* The ship's positional track was in substantial agreement under all conditions.

- \* The simulation of the propulsion machinery agreed well under all conditions. The simulated responses looked reasonable for all components down the drive train.

- \* The ship's heading showed a greater degree of variation in one model. The difference was variable, and was less under the influence of lower environmental conditions.

- \* Only steady environmental conditions were used.

b) Verification of Other Functions. A number of areas of the new simulation's functions were not covered by the Database, and hence verification proceeded as follows:

- i Machinery State Control: for both primary and auxiliary machinery the simulation provides state control using the start/stop signals. For these simple functions a functional check was sufficient.

- ii Towed Body Dynamics: alternative data was not available. Verification was thus by inspection and acceptance of the simulation's results.

- iii Environmental Dynamics: the SRMH Database sets out the characteristics expected for the dynamic parts of the wind and wave environments. With no alternative sources of data available, verification was by inspection. The simulation of the dynamic effects for the wind and waves displayed a reasonable response in their time series. Their frequency content was estimated using typical data sets, and compared with that specified by the SRMH Database. This confirmed that the software implementing the environmental dynamics was consistent with the requirements of the SRMH Database.

- iv AIO Subsystem: Verification was completed by functional inspection and testing only.

As a result of this activity the simulation model was accepted as a basis upon which to embark on the trials programme. At the time, it was recognised that quantified data may be expected from SRMH-01's sea trials programme. Undefined Trial U6 was specifically defined to provide data from the simulation model that may be useful in such a comparison with ship derived data.

c) Comparison with SRMH-01. After the Contractor's Sea Trials of HMS Sandown, some information on its behaviour became available, and allowed some comparison to be made. This gave some view on the degree of agreement between the simulation model, and the real thing, thus completing the validation process. The main points in the comparison made to date are as follows:

- \* It was suggested that the simulation model has a more damped response than the ship.

- \* Data from trial U6, and quantified comments made by Sandown's crew, gave comparable results for stopping distance, and steady state turning speed.

- \* The ship's heading showed less movement in response to the wind and wave environment than the simulation model.

- \* Observations suggested that hover by Position Control by Manoeuvring (PCM), and track keeping performance, were at least as good, possibly better, than that shown by the simulation under similar conditions.

The agreement noted at ii) gave some confidence that the models broadly agree with the ship's performance. The conditions of the comparison in the case of i) are ill-defined, and could arise from variation, for example, in the VSP rate limits in force. In the case of iii) the environment's dynamic effects are identified as a potential cause for concern. Further data is required before a more complete statement can be made about this last stage of validating the simulation model.

#### 4 THE TRIALS PROGRAMME

##### 4.1 Planning the Trials

By testing and assessing performance in isolation from the actual ship, there is the potential to execute a wide variety of trials, involving extreme conditions. The wind and tide environment is controllable and repeatable, a feature not found in a seaborne trials programme.

The assessment criteria, and the trials programme must reflect the requirements for the Machinery Control and Surveillance (MCAS) and the Ship Position Control System (SPCS) for the SRMH. As a result, the definition of the trials was built up using both the original requirements documents, and a general appreciation of the needs. An important input was the knowledge of operational aspects provided by a Naval Trials Officer. Documents produced later than the original STRs were not used, either as a basis for planning the trials, or in assessing the results.

During the planning of the trials, an appropriate documentation system was set up to ensure that each trial's procedure was fully specified, and that all relevant data was recorded. This information was set out in the form of 'Trial Definition' documents which were formally approved following comment by JTT members.



#### 4.2 Structure of the Trials Programme

It was recognised at the outset of the work that most, but not all, of the trials could be identified beforehand. As a result, 'Defined Trials' and 'Undefined Trials' were set up.

The Defined Trials exercised all aspects of the systems' functionality. This gave a broad view of the performance of the equipment in a operational setting. They were planned as a programme of exercises of increasing complexity, allowing familiarity and confidence to be accumulated. This 'bottom-up' approach resulted in two distinct campaigns, designated 'A' and 'B'.

Campaign A, exercised subsystem performance, and assessed the equipment against purely functional requirements, where each is exercised in relative isolation from others.

Campaign B built upon Campaign A by exercising the equipment under conditions that approached operational conditions as far as possible. This included failure conditions, changes in control modes and representative operational sorties. Previous experience had shown that some operator training was needed before such exercises could be undertaken.

In support of Campaigns A and B was:-

Campaign L identified observations that are made during other trials activity, such as ARM data. This approach allowed such data to be accumulated and reported within the trials documentation structure.

Undefined Trials (Campaign U). It was expected that some uncertainties, irregularities or other points of interest would be identified during the Defined Trials, together with a desire to investigate them further. This was the purpose of the Undefined Trials. Their content and form was only defined as the need arose. Typically these trials exercised certain functions in more depth and across a wider range of conditions than the Defined Trials.

This was the structure in which the trials programme was executed. After the completion of equipment setting to work and team familiarisation, campaign A was completed in about four weeks. After a short pause, campaign B was completed in a further two weeks. It had been expected that a break of six to eight weeks before the start of Undefined Trials would be possible. This would have allowed the reporting of results, and further planning to be carried out. In the event, the pressure of time on the programme meant that the Undefined Trials started immediately, and ran through without a break until trials activity was curtailed when the equipment was removed for use elsewhere in the SRMH programme. Trial activity finished in early October 1989.

#### 4.3 Defining and Reporting the Trials

Documentation was prepared in advance of the execution of every trial, in the form of a full definition, and each trial was the subject of a separate results report.

a) Trial Definitions. The Trial Definitions for all the exercises made use of a set of Standard Operating Procedures (SOPs). These were set up before the trials based on standard orders, as adapted for the SRMH's needs by the Trials Officer. The adaptation was based on an expectation of how the system would be operated.

The definitions were produced by expanding preliminary information to include all details necessary for the execution of each exercise:

- Index: detailing the individual documents within the definition.
- Trial Specification: describing the objective(s), assessment criteria, and procedures for the trial.
- Initial Conditions.
- Procedural Definitions, in terms of activities and SOPs to be carried out.
- Execution Records: proformas used to record execution.
- Data Recording: command files to set up the data to be logged.

b) Reporting. During and following the Trials programme, the results, assessment and recommendations were reported as follows:

- i Trial Results: these reports contained the data and information gathered during the execution of each trial.
- ii Assessment Reports: summarised the assessor's view of the results obtained, and recommended further action or Undefined Trial proposals.
- iii Interim Report: summarised the results of the Trials carried out, and included an early interpretation of the results and implications on system performance as a whole.
- iv Final Report: presented similar information as the Interim Report, but extended its scope to include all aspects of the work programme.

#### 4.4 Execution of the Trials

For the execution of the trials, the roles set up within the trials team were:

- \* Trial Controller, running the simulator;
- \* Trial Operator, operating the consoles;
- \* Trial Observer, as needed to monitor and record execution.

For some exercises one person could fulfil all these roles, for others (eg the sorties) a team of three or four was required. Some specific items of procedural support were found to be particularly beneficial:

a) Trial Scripts. A 'trial script' command file was set up for each exercise from the Trial Definition. This script file formed an additional level of documentation, containing a precise statement of all of the commands that were used to execute each exercise. The file was read, with instructions being passed to the operator by means of SOPs. Procedures and actions were set out in the form of commands for the simulator's user interface with the precise syntax required. In many cases, exercises were repeated to demonstrate consistency, or to eliminate non-repeatable events contaminating the results. In addition, where significant observations were made, the exercises were repeated to provide the required confirmation.

b) User Interface. A vital component in the effective execution of the trials was the window-based user interface. Its effectiveness was based on:

i The use of the mouse to transfer text from one window to another. This virtually eliminated the need for the Trial Controller to type commands during the trial. This eliminated errors, and allowed the Trial Controller to concentrate on monitoring the execution of the exercise.

ii Any correction or modification to the commands or sequence of execution was done by editing the script. The script then remained as a permanent record, and was available for repeating the exercise if required.

iii The "comment" signal allowed the Trial Controller to add comments into the log file. Scripts and command files also used this facility. This gave a time-stamped commentary of the execution of the exercise when the comments were processed into a single text file.

iv The extensive use of command files within the window environment meant that, once the files were established, there was no penalty in setting up complex conditions. Other scripts or fragments could be easily copied for re-use, allowing trial scripts to be worked up very quickly.

c) On-Line Disk Filing System. To accommodate and organise the large number of command and data files generated and used during the trials, a hierarchical file store was set up. This file store had the following parts within an overall directory:

- i Directories for generic command files including:
  - data recording definition command files;
  - initial condition command files;
- ii Directory for each trial containing sub-directories for:
  - data files logged from each exercise;
  - script command files;
  - processed data files created by the off-line facilities.

Command files were generally in text form and were created and maintained using Unix text editors.

#### 4.5 Comments on the Trials Programme

The trial programme was made up of twenty two trials defined during the course of the work with a range of objectives. In this section, we survey each of the trials to provide an overview of the contribution made by each to the programme as a whole.

##### a) Campaign A

**A1: Machinery Control Functions:** these exercises served to establish a baseline of functionality, and to act as a confidence measure confirming correct system integration. Few comments were made, and those that were, reflected the satisfactory nature of the system design.

**A2: SMS Manual Control Functions:** these exercises served as a similar 'benchmarking' function as A1. Additionally, they acted to confirm the familiarity of system operation on the part of the trials team.

**A3: Indications, Alarms and Warnings:** As with A1 and A2, the basic functionality of the equipment was confirmed in these exercises.

**A4: Hoverplan Display:** A 'static' review of the information presented by the hoverplan against the demands of the original Statement of Requirements (STRs). As with A1 to A3 the baseline functions were confirmed.

**A5: Ergonomics:** this trial produced much valuable information. This was largely the result of being one of the first occasions to use the new standard DEF STAN 00-25 as an assessment tool. Although the DEF STAN was not a contractual requirement on the designers, it was shown to be a useful benchmark with which to review the equipment ergonomics.

**A6: SMS Automatic Control Performance:** this trial, executed without the random effects of environmental dynamics, allowed a baseline of capability to be observed and gave confidence in the system's operation.

**A7: SMS Response with Environmental Disturbances:** this trial successfully achieved its objective of providing the first complete view of what the ship would do under automatic position control. As such it was rich in data.

##### b) Campaign B

**B1: Command Mode Transitions:** relatively little came out of this trial for two reasons. Firstly the requirements had been met by the system design, and Secondly, the transitions were so straight-forward that there was little scope for operator error.

**B2: Failure Modes:** This trial confirmed that the relative simplicity of the SRMH systems meant that complex failure modes do not occur. The involvement of the operator in responding to failure modes was low. For the range of relatively simple failure modes explored much useful data emerged.

**B3: Operational Sortie Exercises:** As expected these exercises proved to be very rich in data, and raised several issues for review. In execution they proved much more time consuming than expected, and would have benefited from extra preparation and additional facilities such as monitoring position in real time.

**c) Campaign U**

**U1: CVL Performance and Failure:** In line with expectation, this trial provided useful information on the baseline capability of the system's response to variations in the quality of data provided by the CVL.

**U2: Transition between DP and PCM in Hover:** The execution of this trial provided much valuable data of importance to the ship's capability.

**U3: Performance of SPCS issue 2 software:** This trial added a level of confidence to the conclusions obtained earlier. The exercises showed the good repeatability obtainable within the trials programme.

**U4: Manoeuvring Between Closely Spaced Waypoints:** This trial successfully explored an area of performance that had not been envisaged in the original requirements. The results obtained were rich in data for assessment purposes.

**U6: SRMH Turning Data:** The value of this trial is dependent on comparative data being obtained elsewhere from the ship's programme. By presenting data in a 'user-oriented' form, it provided a further focus on the model validation issue.

**U7: Operating Mode Review:** this activity was useful in allowing a further opportunity for the views of the user community to be fed into the assessment.

**U8: Operational Manoeuvres:** this trial was successful and the results rich in data to provide further coverage of the issues thrown up by trial B3. The information provided has value beyond the assessment programme, particularly for the ongoing development work of the designers.

**U9: Additional Exercises:** this trial was very rich in data, and provided a prime example of the 'Undefined Trial' concept. The exercises explored several specific observations made earlier, and were based on previous exercises. The experienced trials team used the command file libraries to define and execute the trials in a very short space of time. This was done without compromising the quality of the documentation or traceability established throughout the trials programme.

**d) Campaign L**

The campaign L activities were recognised as essential 'across the board' reviews in specific areas. Although a limited amount of information emerged it is felt that they served their purpose well.

**L1: ARM Data:** this activity achieved its objective in collecting small but useful amount of data in the area related to the achievement of ARM targets.

**L2: Machinery Demand Assessment:** with potentially a huge amount of data to review (from all trials) this activity illustrated the value of careful selection of data for analysis later. A valuable interpretation of the selected observation resulted.

**L3: Operational Ergonomics:** As with L2 a great deal of valuable information was accumulated and organised in this activity. Most of the was observational and anecdotal.

**L4: Support Studies:** this activity was recognised as a useful home for observations and comments of relevance, and was recognised as a purpose well served. This may be interpreted as confirming that no substantial issues were omitted from the assessment.

## 5 CONCLUSIONS

At the end of this assessment, the result was a positive answer to the initial objectives. However, more questions were raised for the respective Ministry Projects to ponder. The Undefined Trials programme provided the answer to some of these questions, but many were left open, and require investigation. These aspects could not be addressed due to equipment availability and other constraints placed upon this work.

The value of Assessment projects are not easily quantified in time and monetary terms. The confidence gained from the operation of new equipment during an assessment is invaluable experience to all concerned. Having assessed one particular system design, it is unlikely that a repeat assessment would be needed. Ship design and build programmes often being in the order of ten years duration, the chance of the same system design being used for follow on ship designs is rare.

Therefore, assessment should be used as a tool for design support. The justification and reasons for such an approach become stronger as the complexity of control and surveillance systems increase, and the move is made towards management systems.

Reference [3] identifies the case, and makes the recommendation for, a Shore Based Test Facility being established as during system development, in order that assessment becomes an integral part of a design programme.

Specific points did come from other issues around the Assessment:

\* The involvement of the 'user community' through the participation of the RN Trials Officer proved most useful.

\* The process of verifying and validating the simulation model showed the importance of alternative and independent data. The data from the trials, including that from the validation exercises, should be compared with 'ship data' when available. The result of this comparison should enable improvements to be made to the simulation model. Any further assessment trials should be defined with a greater recognition of the potential disagreement between the simulation model's behaviour, and that of the ship.

\* The amount of data collected was awesome but, because of the documentation and user system structure, it was found to be controllable. This became important and most evident when carrying out the Undefined Trials. Trials were defined, executed and the results captured very quickly, typically in less than a week, without sacrificing quality, consistency and traceability.

\* The user interface flexibility and effectiveness cannot be praised too highly. The time and effort spent in defining and implementing these facilities proved to be well worthwhile.

\* The review of results data needs further procedural support in order to reduce the effort required. Serious consideration should be given to some means of sifting data automatically rather than manually, and in making early decisions on the analysis required by any dataset.

\* From the volume of data available, the results and assessments were reported quickly, although in many cases this was after the trials activity had been completed. Both underline the importance of having effective maintenance of the documentation records in support of report production. In addition, a comprehensive word processing facility is regarded as an essential component.

\* The success of this project would not have come about without the willingness and good understanding built up between the engineers involved. All the rules, procedures, controls and documentation cannot replace a good working relationship, and the commitment to success.

## 6 DISCLAIMER

The results and opinions expressed in this paper are those of the authors, and do not necessarily represent official policy.

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## CONDITION MONITORING AS AN INTEGRATED ENGINEERING SUPPORT FUNCTION

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### 1. ABSTRACT

Existing marine condition monitoring programmes are limited in their effectiveness by operational constraints, system design and the lack of a common environment to act as a highway between condition monitoring systems, operational/control data and management scheduling tasks. A study undertaken by the Royal Navy and YARD Limited and experience gained from commercial condition monitoring projects, suggests that many of these limitations may be overcome by the introduction of a revised Engineering Information Management System. Such a system would integrate a number of condition monitoring, maintenance and management functions, utilising developing communications techniques, sensors, automatic analysis and knowledge based systems.

This paper will review the work carried out by the Royal Navy and YARD Limited in the application of condition monitoring and identify the enabling technologies available to implement an effective marine condition monitoring system with its associated maintenance management system as part of an Integrated Platform Management System (IPMS).

### 2. INTRODUCTION

The requirement to maximise the availability of ships and therefore their engineering systems is common to Navies world wide. Meeting this requirement is variously attempted by the duplication of systems, periodic functional testing to determine availability, retaining large quantities of spares to replace failed components, inspection and monitoring the condition of rotating equipments by the measurement of vibration. Non rotating units are subject to internal inspection and the application of non-destructive testing technology. Within most organisations attempting to achieve the management set objective for availability by the application of these techniques, a delineation exists between that part of the organisation responding to the operational requirements and the support organisation striving to meet the availability target. This delineation of objectives has led to the divergent development of the command/control data handling system and the engineering support system. In part this has been due to the rapid uptake of centralised data presentation achieved for command/control applications when compared with maintenance and support functions. Data

that is presently used for control or engine health monitoring functions is automatically monitored and stored whilst if the same data is required to determine maintenance requirements, it has to be collected manually. The factors which have helped to focus attention on this situation are mainly associated with the introduction of computer based systems for engineering information technology. The introduction of computer based condition monitoring systems requires consistent, valid engineering data to be made available if automatic processing is to be achieved effectively. At the same time, the introduction of software based maintenance management and logistic planning tools has resulted in the maintenance function becoming more visible to management with condition based maintenance seen as the basis for reducing effort and costs across a wide range of naval, commercial marine and industrial applications.

### 3. NAVAL CONDITION MONITORING

Condition monitoring (CM) as the basis for planning maintenance has been an accepted technique since 1970 when it was applied as a formal method in the process industries. The technique was then adopted by manufacturing industries at various rates depending on the skills available, economic pressures and management attitudes. During the 70s CM did not, however, achieve a marked effect in the reduction of routine or calendar based maintenance. Manual recording of data restricted condition monitoring techniques to some performance monitoring of process parameters such as temperature and pressure, and vibration monitoring (limited by the need to physically collect and analyse the data). Each of these measurements may be represented by a single numerical value and when monitored over a period of time may be plotted to indicate a trend. From this historical data the engineer can identify the rate of deterioration of an equipment and predict when maintenance will be required (Fig. 1). The limitations of manually operating such a system are obvious, being both labour intensive and prone to the introduction of errors in measurement. With the introduction in the early 80s of digital data collection systems and CM software packages run on compact processor hardware, a new impetus was imparted to the introduction of CM as a predictive maintenance tool. The introduction of digital data collection units and the ability to store and process the collected data overcame many of the limitations of manual systems. For process plants with widely distributed components and commercial marine systems with reduced manning requiring maintenance to be planned onshore the benefits were immediately recognised. The ability to effectively predict failures and quantify rates of deterioration of mechanical components being instrumental in permitting both maintenance and production scheduling to be planned more efficiently.

### 4. NAVAL MAINTENANCE MANAGEMENT

In parallel with the CM developments in the commercial sector, maintenance practice within the Royal Navy was evolving to reflect the technology available and the changing practice within the fleet. The previous generation of marine propulsion systems, being simple, large and

having massive redundancy by today's standards had little need for maintenance management. The time afforded by the requirement to frequently shut down and clean boilers allowed routine preventative maintenance to be carried out without the need for detailed forward planning.

The introduction of more complex machinery and a change in operational requirements for ships and submarines resulted in the development of a true maintenance planning system becoming a requirement. This requirement was first met by a Planned Maintenance System developed by the Royal Navy in 1953. It was based on the operational cycle of the ship and consisted of a card-based system which specified the tasks and periods at which maintenance was required to be carried out on specific equipments. The major advantage of this system was that Shore Management were aware for the first time of the ongoing mechanical condition of their ships.

There were, however, drawbacks to this calendar based maintenance system. Availability was not improved as increased downtime resulted from both the increased maintenance and from consequential repairs to maintenance induced damage. Continuous development and refinement has steadily improved this system with maintenance periods extended from the original requirements, manpower reduced and detailed job instructions introduced. Culmination of this development was the Maintenance Management System (MMS) which remains one of the components of our integrated management requirement.

While the MMS was being developed, other factors were bringing pressure for change in maintenance practice. The introduction of the Gas Turbine Frigate with its greatly reduced complement and Nuclear Submarines with their inherently high availability propulsion system coincided with an increased awareness of upkeep costs and the need to reduce them. These forces combined in the late 1970s to force a review of maintenance policy.

At this time, some 20 different condition monitoring techniques were in use in the Royal Navy. They were, however, not formally recognised as such and their full potential, derived from presenting the data collected against an elapsed time base was achieved in only a few exceptional cases. In contrast, industry was, mainly due to economic pressures, changing their maintenance policy over to condition based systems wherever possible. In the light of the CM developments in industry and within the merchant fleet, the outcome of the review was clearly in favour of introducing CM to the fleet. The maintenance policy was based on the following principles:-

- (a) Maximum use of condition based maintenance
- (b) Critical examination of maintenance requirements against the operational needs
- (c) Overhaul and repair action to be taken at the lowest sensible level.

These principles were incorporated into a formal policy for the fleet in 1980. This was ahead of the personal computer revolution which was just starting. The system relied on manual data collection and the tools available at that time were of limited capability and it was not possible to implement the policy in full.

Where progress was made was in the application of vibration monitoring techniques. From the large complex specialist equipment used in the 60s and mid 70s, hand held units were developed for point measurements. Subsequently, ships were also supplied with compact vibration analysis equipment to permit the regular collection of accurate overall vibration levels. These systems still required manual logging of data to identify trends and it was not until 1986 that the first computer based CM system was installed in the fleet. These units were provided as part of the Naval Condition Monitoring Trial to demonstrate that computer based CM could be effectively applied to Naval equipments.

#### 5. CM SYSTEMS

The form of the CM systems installed was typical of commercial products applied in industry. This comprised three main components, the data collection unit (DCU), a personal computer (PC) and a CM software package. The DCU was a solid state device, having the facility to collect vibration data via a hand held probe and the manual input of process values via a keypad. A small solid state display identified the measurement locations to be monitored and permitted validation or interrogation of the data collected. The main task of the DCU was to store the collected data and download the data with time and location labels to the PC. The PC was two main functions; one, to programme the DCU with the selected measurement point route and two, to manage the collected data and, utilising the CM software package, present the data in a form suitable for interpretation by an engineer, (Fig. 2). The software package provides the facilities common to many such systems including collection, storage, processing, presentation and reporting facility. It is not, however, the considerable power of the processing software which is the most important factor achieved by the introduction of these systems, and which will change the form in which CM is applied in the future. It is the step from documented to digital storage of the data which will permit further processing and access by other processor systems without data corruption or a penalty in effort permitting integration with other IT systems. The initial manual collection of data into the DCU may be replaced in part by hard wired transducers, however, for many applications a manual DCU system will be cost effective and meet the objectives of obtaining repeatable, accurate data.

#### 6. DATA HANDLING

Given the preceding CM system components, we can configure a system to give a first level of assistance to the engineer. Automatically the system will check for excursions beyond preset levels, indicate trends based on previously stored values, present comparisons with baseline data and

process data to detect specific modes of deterioration associated with mechanical components. The interpretation of data in this form still requires the expertise of the engineer to convert data to information from which engineering actions may proceed. While this expertise will remain a requirement for resolving complex analytical problems, the present level of routine manual interpretation is determined by the limited process status and functional performance information which is available to the CM system. This information is available in the 1000 parameters per day monitored by existing command systems. This information is presently utilised by the command system at the application level required for control and health monitoring and is processed at near real-time rates, selected parameters being screened at 400 parameters/hour. Manual logging of these same parameters for CM applications is obviously inefficient and also limiting in the effectiveness of CM applications due to many of these parameters not being duplicated with local display facilities. There are, however, restrictions on using this data. Access to the data collected by existing command systems is limited by the form of processing applied. Large volume, long term storage and secondary processing is not a common requirement for most command systems. Historical data is normally utilised by the command system to determine fault conditions over a period of hours rather than months of data collection on which CM trends may be based.

CM is not the only system where benefits may be gained by having access to the present command system data. Given a suitably compatible form to permit automatic off-line processing, a number of engineering and management tools will manipulate the data for their specific applications. This may be in the form of utilising CM and process data to determine future CM needs, enable assistance to be supplied by specialist authorities, optimisation of performance, feedback to designers or interfacing to other management levels. All require consistent data in order to be effective and to assist ships staff by supplying support services in a cost effective manner.

#### 7. DATA PROCESSING

To permit access to the basic data required by the above systems requires a structured operating system with suitable levels of intelligence applied at each application level. First level intelligent processing will validate the data base, correlating with equipment operating conditions and process parameters. Second level will associate faults with parameter values and consider the confidence level available for the conclusion. Third level intelligence will act as the common interface for the various levels of information requested and the interactive component operating between each of the engineering systems (Fig. 3).

##### Level One

At the first level of data processing the CM requirement relates directly to maintenance requirements. The data collected will be processed to determine that the equipment is operating within acceptable limits and

identify the formation of trends for specific parameters. Data common to the command system is required to enhance a number of functions associated with achieving these two aims. Data relating vibration levels to equipment operational conditions and system boundary conditions permits greater relevance to be placed on both single value and upon derived trends. The operating configuration of systems local to the equipment being monitored also allows for the extraction of non-relevant data. The operating profile recorded for equipments permits the scheduling of data collection tasks to be optimised on an equipment usage rather than routine calendar based periods. Even at this most basic level of CM there is, therefore, a requirement for automatic intelligence to be applied and for data derived from the command system to be available without recourse to its manual entry into the CM system.

It is also from this first level that database information is established which subsequent higher levels of analysis will utilise to determine system operational and performance capability and to assist the engineer in the determination of specific malfunctions. A key to ensuring that this may be achieved is the configuration of the CM database in a format which provides sufficient flexibility and standardisation to permit access by multiple users. The validation of data prior to entry into the database is also important and the application of validation techniques incorporating elements of automatic intelligence will be required to handle the range of parameters derived from engineering systems. Pre-processing of data from non CM system sources will also be required to ensure conformity with the CM database. The form of pre-processing will recognise that, unlike the health monitoring and surveillance task carried out by the command/control system, CM is not a real time data processing task. CM data is therefore collected at less frequent intervals and may be processed and stored in a reduced data format. This requires both steady and non steady state data, such as that derived from equipment during initial run-up, to be reduced to a suitable format for storage and comparison with baseline data held in the system database.

#### Level Two

At the second level of CM data processing the need for interaction between the CM function and the command/control system becomes more visible. The present division of primary/secondary control and primary/secondary surveillance does not immediately lend itself to the easy integration of existing systems with other management functions. Achieving this is a further reason for removing existing functional boundaries within these engineering systems, recognising at the same time the need to integrate CM functions. The need for this integration is a function of second level data processing content, being directed at presenting information at the user interface rather than collecting data for interpretation. The information to be presented is dominated by two main requirements. The first is directed at the need to advise management of the operational condition of systems and the anticipated rate at which their availability will change. The second is the need to assist the level one task operator with the

identification of specific fault modes and apply a degree confidence to the diagnosis for maintenance planning requiring shore based assistance. The need for engineering management to be aware of the physical condition of marine systems is a major factor in determining the level of maintenance to be carried out. Lack of knowledge on condition will result in over maintenance in an attempt to ensure that mission requirements can be met or to secondary damage arising from equipments being stripped for inspection. This need to have information on condition relates to both mechanical health and to application health. The first is partially met by existing CM techniques with limited use of process parameters and is applied mainly to rotating equipments. The form of this data requires interpretation in an automatic form to reduce operator effort. The second requirement, that of application health, is presently only met by specific performance tests i.e. how long does it take to fill the air receivers from empty. There is a high penalty in effort for carrying out tests of this type and the information recovered is minimal. With the integration of the command/control system data with intelligent components of a CM system, the automatic testing of such systems becomes a reality, with the need for specific tests being limited to validation of the monitoring system. To achieve the reduced level of effort requires the application of advanced data processing techniques. Based on an existing AI shell, this has been achieved on models incorporating elements of intelligence to handle the complex interactions inherent in moderately simple equipments, demonstrating the potential of these systems as engineering information tools. However, these initial systems were directed at relating data to specific components i.e. gears with identifiable sidebands or bearings with well defined frequencies relating to their rotating elements. These systems did not relate to process faults and were suitable only for rotating components and mechanical health. The development of an equipment or system model incorporating these techniques becomes a more powerful tool with the potential for automatic diagnostics at component, equipment and system level.

### Level Three

As discussed, the first two levels of data processing are specific to determining the condition of the equipment or system and managing the data handling task required to utilise information from the integrated management system. To permit full integration of CM systems within other marine systems requires that a further level of data handling capability is introduced. This third level is implemented to provide the common environment for the export of CM data to other engineering systems and to permit the import of data derived from other sources. Within the ship operating unit, the associated engineering systems include maintenance scheduling tools, reporting tools, stores requirements and operational capability information systems. Outwith the ship, information is required by specialist maintenance units, centralised design authorities, stores systems and logistic support programmes. Imported into the system will be CM application software revisions, supporting database information from other ships, modified maintenance procedures and CM methods and instructions modified by experience and changing requirements. The single common factor handling these separate software packages will be the common environment.

Experience dictates that all packages interfacing with the common environment will have the capability to operate or be modified without directly impinging on the operation of other application packages, ensuring integration without the loss of flexibility associated with large multi-application software tools.

#### 8. CONCLUSION

Experience gained in the operation of computer based condition monitoring systems applied in surface ships and submarines over a three year period has clearly demonstrated the need for CM to be integrated with other engineering management functions if full benefits are to be achieved from both IPMS and CM. Integration of these systems requires to be progressed at two levels, technical and managerial. Work undertaken in the Royal Navy has demonstrated that the three principal components of the technical requirements can be effectively applied with existing commercial software tools and by further development of presently available demonstrator tools;

: Commercial computer based CM systems have operated satisfactorily, but highlighted the need for tools to assist in interpretation of data.

: Utilising a hand held programmable electronic notepad the principle of collecting and automatically processing watchkeeping data has been demonstrated to be both efficient and effective. The need for integration of this task to present the data in a format required to meet operational support and CM functions is a logical extension of this work.

: The application of intelligent systems as tools to reduce analysis effort and enhance the interpretation of both process and CM data has been shown to have practical benefits both in ensuring that data is processed to gain maximum information and to bridge the engineering/management gap.

The development of management tools which form part of an integrated system extending beyond the direct engineering application both onshore and in the ship will achieve both the cost/effort reduction requirement and meet the management education needs. Lack of detailed information on maintenance tasks limits the effective use of reliability, cost analysis and logistic support tools. This has a secondary effect in limiting management interest due to a lack of visibility. The integration of all components associated with maintenance within an integrated platform management system will overcome this barrier and result in maintenance practice being developed alongside ship management systems.

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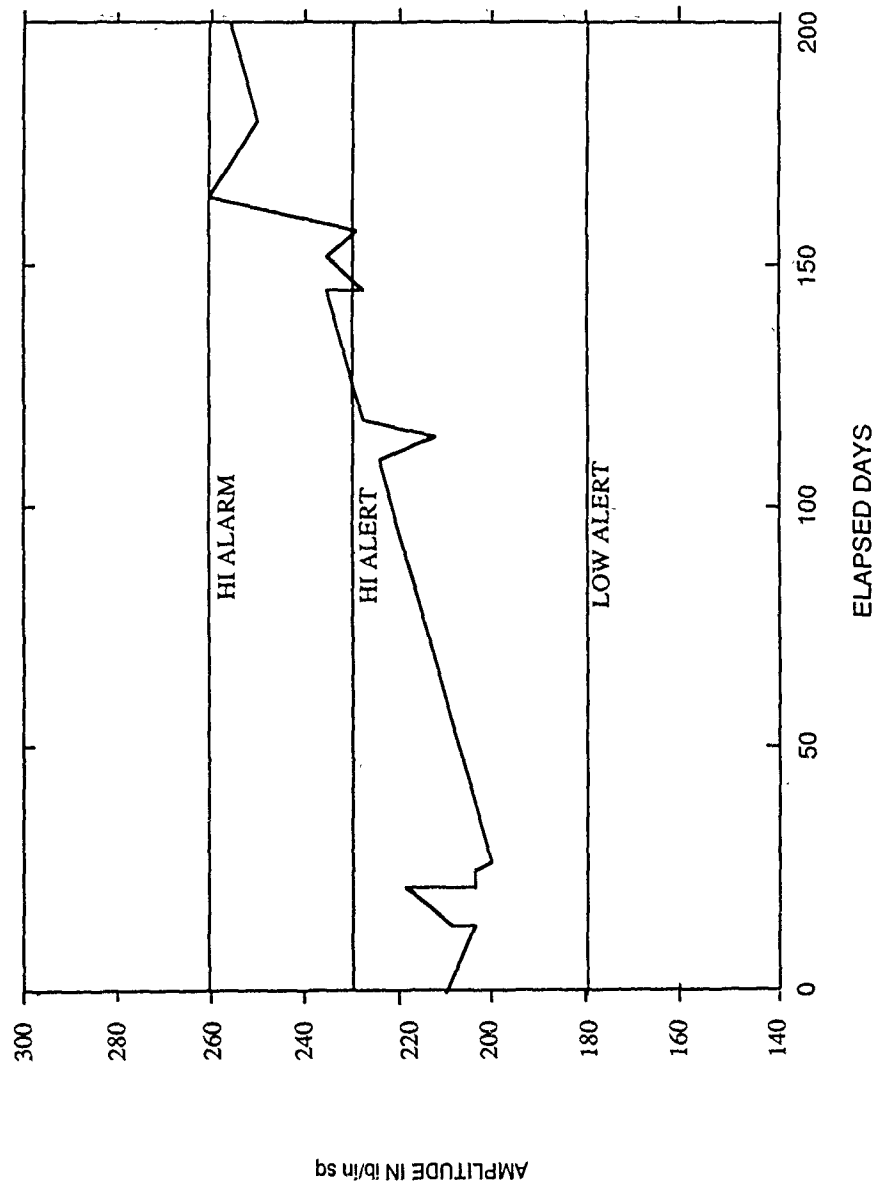


Figure 1 - Air Compressor interstage pressure logged and trended to identify the development of a defect in the following stage valve

# Intelli-Trend(R) Multi-Trend Display

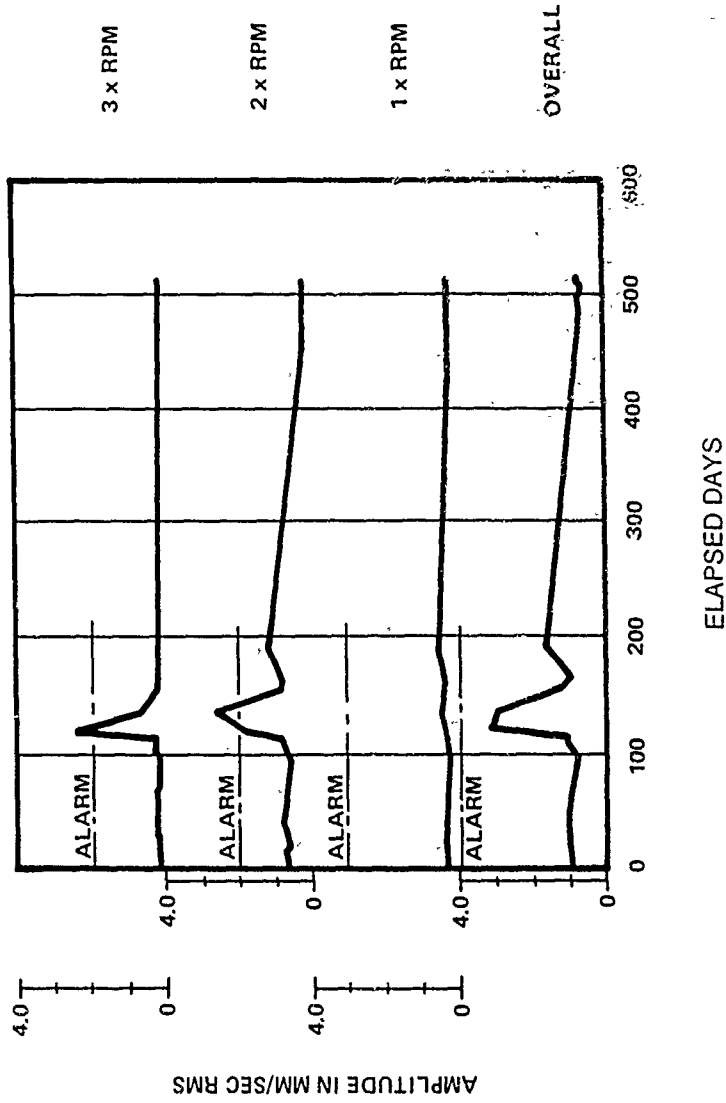


Figure 2 Increased vibration levels associated with the deterioration of a rolling element bearing on a marine electrical equipment identified by routine CM. Bearing replacement resulted in subsequent reductions in vibration levels.

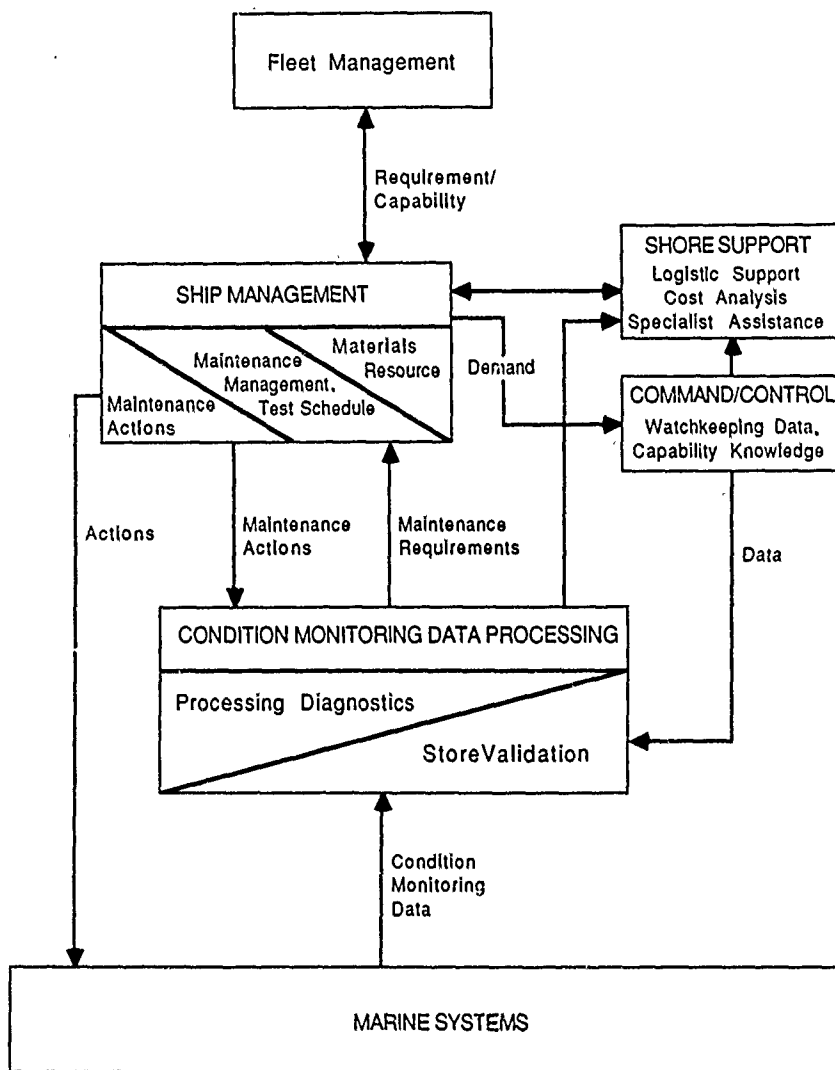


Figure 3 - INTEGRATED ENGINEERING MANAGEMENT SYSTEM

## DIESEL ENGINE CONDITION AND PERFORMANCE MONITORING

by A.J.DAVIES  
Marconi Command and Control Systems Ltd

### 1. ABSTRACT

Recent advances in computing techniques in fields such as simulation and artificial intelligence offer a widening scope for automation in machinery operation, control and maintenance.

The Diesel Engine Condition and Performance Monitoring System (CPMPS) project was established to develop an on-line marine engine monitoring and management system having five main functions: assessing the condition of the engine, diagnosing faults, monitoring the engine's performance and fuel efficiency, optimising its performance, and prediction and planning of maintenance activities.

In the system, a small number of strategically-placed sensors gather data from the engine throughout its combustion cycle, and this is used to assess its condition and performance. Advice can then be presented to the operator for optimizing operating settings, maximizing fuel efficiency, correction of faults, and scheduling of maintenance.

Novel features of the design approach include the use of expert system techniques for all of the above functions, including the selection of sensor-sites; and also the on-line use of mathematical simulations of engine behaviour both to provide reference conditions for the condition assessment and fault diagnosis processes, and for confirmation and quantification of those diagnoses.

### 2. THE CPMPS PROJECT

The CPMPS project is a program sponsored by the U.K. Department of Trade and Industry, and designed to investigate the practicability of using advanced techniques in the fields of simulation and artificial intelligence to implement a performance and condition monitoring equipment for marine diesel engines. The work has been carried out over the last three years by a consortium consisting of Lloyd's Register of Shipping, the Marconi Company,

and the marine engineering departments of the University of Newcastle-upon-Tyne and Humberside College of Higher Education, with support from a committee of ship owners represented by Shell International Marine, and other Universities and consulting agencies.

This paper reports on the experiences of the project to date, and shows how the different elements of the design have been integrated into a prototype on-line implementation.

### 3. PERFORMANCE AND CONDITION MONITORING

It is necessary at the outset to draw a distinction between Status Monitoring and Alarm equipments, and Performance and Condition Monitoring equipments. The former types of system are well established and meet strict standards for safety and availability. The purpose of these systems is to detect failures as quickly as possible, and to protect the vessel and crew from loss or damage which would be the consequence of such failures, or of continued operation in such circumstances. They must be simple, safe and unequivocal.

However, an engine alarm generated by the failure of a component will have come too late to prevent the possibly considerable cost of a long period of inefficient engine operation due to its running with a degraded component, or to its gradual pre-failure deterioration. It will also undoubtedly occur at a time when recovery and repair is least convenient and most costly. Furthermore, it may give no indication at all for certain engine conditions which may be caused by combinations of degraded but not actually failed components.

What is required in these cases is a system which will provide an ongoing assessment of the condition of the engine, and of its performance under different operating conditions, so that its operation can be optimized at all times, fault conditions can be predicted early on, and effective maintenance activities can be planned well in advance.

The aims of the system envisaged by the CPMPs project are:

- (i) to reduce or remove the cost of unpredicted and unexpected failures,
- (ii) to improve engine availability and reliability,
- (iii) to optimize the operation of the engine, and
- (iv) to enable effective maintenance and repair planning.

The achievement of these aims will lead to:

- (a) reduced running costs and improved fuel economy,

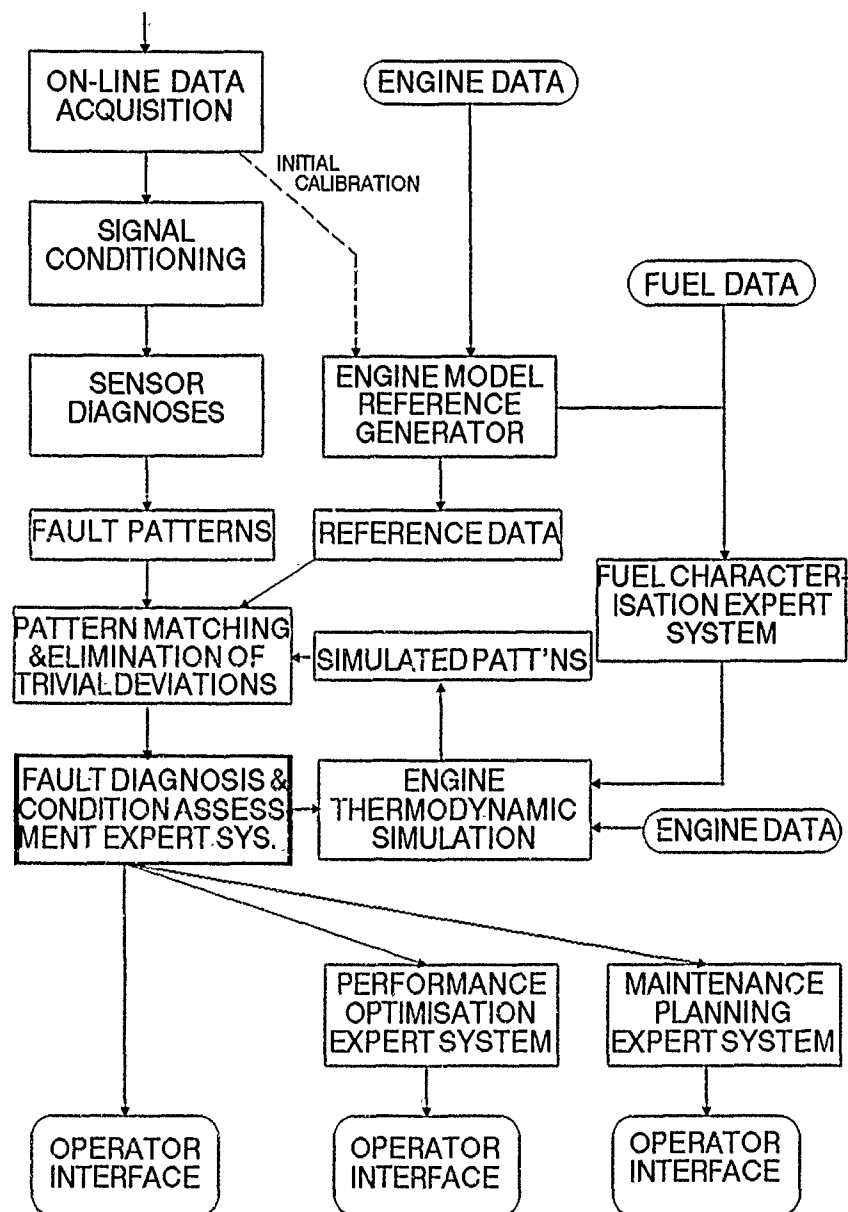


Figure 1: CPMPS Block Diagram

- (b) reduced maintenance and repair costs, and
- (c) better utilisation of engineering personnel.

The means by which the system seeks to achieve these aims is by firstly measuring the performance of the engine using information based on the online monitoring of selected parameters, and then deriving an assessment of the condition of the engine, and attempting to diagnose the existence and severity of specific component conditions.

#### 4. PROJECT APPROACH

From the outset the aim of the project was to derive the knowledge base for the expert system which assesses the engine's condition from actual data obtained from the engine, and to use heuristic knowledge to refine and set into context rather than as the central basis for knowledge. Similarly, the engine simulations used during development and in the online system have been refined by comparison with, and calibrated against, the actual measured performance of the engine.

Information recorded by Lloyd's Register regarding the main failure modes of about 2,500 slow and medium speed engines built and operated during the period 1970-1981 were studied, and from this information a total of 80 faults and fault conditions were selected for inclusion in the investigation. A 750 RPM 6-cylinder marine diesel engine at the Newcastle Site was chosen as the testbed, and this was instrumented with about 200 sensors and measuring devices.

The first stage of the project involved many hundreds of hours of engine testing and data collection. At first the engine was completely overhauled and run in "reference condition", to calibrate the simulations, and set the reference patterns for later deviation analysis. Subsequently, a predefined series of faults were introduced, for example by machining measured defects into various components to simulate wear or distortion, and measuring the performance of the engine via the sensor readings in each case. Some 300,000 readings were recorded for each "sample" run.

Because of the large amount of data collected, automatic means of processing the data were used on the development computers, resulting in the selection of a minimum set of "useful" sensors; the derivation of a characteristic pattern of sensor readings for each fault; a set of rules for recognising and discriminating between each of the faults; and values for the natural variability and sensitivity of each of the sensors.

This information was then used to provide the information source and rule base for the fault diagnosis expert system. This

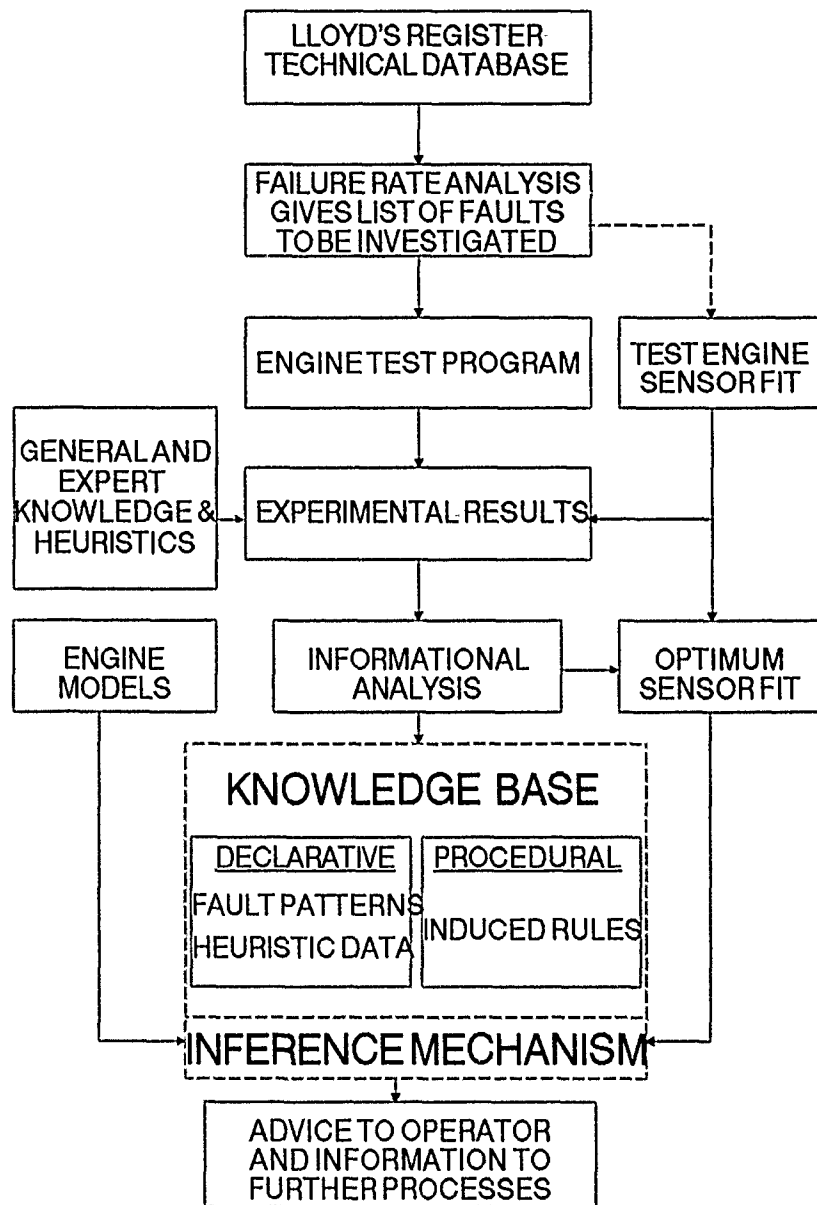


Figure 2: CPMPs Project Approach



forms the hub of the CPMPs system, as shown in figure 1. Each of the individual processes in the system were tested off-line by replaying into them the recorded measurements from the engine trials. Finally, each of the subsystems were integrated together onto a single computer system and tested online by attaching "live" to the engine and running diagnoses and assessments in real time.

A summary of the development approach is shown in figure 2.

## 5. SELECTION OF SENSORS

The selection of sensors and their siting in the system are based on a number of considerations, which may be summarized as:

- (i) The minimum number of sensors should be chosen which allows the maximum level of fault diagnosis;
- (ii) All sensors should as non-intrusive as possible, both to remove the cost of adaptation of engine components for sensor fitment, and to eliminate the possibility of degradation of component performance or reliability by such adaptation;
- (iii) Sensors should be used which are as inexpensive as possible whilst retaining adequate performance and reliability in their working environment.

The final placement of sensors in the system was done partly by reference to expert knowledge, and using statistical information obtained from the records of Lloyd's Register of Shipping; but was mainly the product of the Rule Induction process:

During the initial testing phase of the product engines at the two testing sites were instrumented with a total of more than 200 sensor points, some of which were manually observed, but most of which were recorded automatically by computer. Readings were taken from all the sensors at each operating point of the engine, and at each induced fault condition. Subsequently - offline - rule induction techniques were applied on the data accumulated to identify that set of sensor readings which were significant in each of the tests, and in particular which subset of those readings were necessary to distinguish between the diagnoses of each of the faults.

There is also a need, however, to provide a certain amount of redundancy in sensor siting, so as to give some degree of corroboration of each sensor reading by alternative indications or by nearby effects, especially where sensors are particularly critical, or may be particularly prone to failure or damage due to difficult operational sites or less robust technology. In the event, a total of some 26 sensors were selected as being "diagnostic", although about 100 were monitored in the final system, as providing useful or corroboratory evidence either to the

diagnostic system or simply as a direct display to the operator to provide extra confidence in the diagnosis.

The majority of the sensors used in the system are thermocouples, or piezoelectric or strain gauge pressure transducers, although the effects of more sophisticated measurements such as fuel abrasivity and wear debris content have also been considered. One of the most useful measurements, however, is to record the pressure readings in the cylinder throughout the combustion cycle (synchronizing the readings to increments of the crank shaft angle). During the experiments these measurements were made using pressure transducers embedded in the firing cylinder (connected to high-speed analogue-to-digital data acquisition circuitry). However, results obtained from transducers mounted non-intrusively (on the indicator cocks) have been shown to compare favourably with these readings and would almost certainly be used rather than embedded sensors in a commercial installation.

A number of mathematical techniques are used in the processing of the readings taken from the sensors to ensure their integrity, and to facilitate the identification and diagnosis of possible sensor faults, so that the associated readings can be eliminated from the subsequent engine assessment and diagnosis processes. (See Banisoleiman (1)).

## 6. SIGNAL CONDITIONING

In the data acquisition phase of the CPMPS cycle we distinguish between two types of data. "Steady State" data refers to measurements which, once the engine has attained a particular steady operational state, remain relatively steady themselves, at least throughout the combustion cycle. "High Speed" data is that which varies through the combustion cycle, such as the in-cylinder pressure. This latter data has to be captured and recorded by the computer at high speed (in this case, at every 1°-degree through the cycle). However, we are actually looking for specific items of information within the data (such as the point of maximum pressure), so that the system has to extract this information, and pass it on to the diagnosis task, and to the fuel assessment system.

Each item of information, either extracted from the high-speed stream, or taken as an individual reading from the steady-state sensors, has a variation associated with it, and the system calculates Maximum, Minimum, Average and Standard Deviation for each. Excess variability in a reading may itself be a problem indicator (this information also proves useful for sensor diagnosis).

## 7. CONDITION ASSESSMENT AND FAULT DIAGNOSIS

One of the main advantages of the "human" approach to situation assessment is the flexibility with which a number of different techniques and areas of knowledge can be brought to bear to arrive at a final judgement. A number of Artificial Intelligence techniques which attempt to take advantage of this type of approach have been applied in this system.

The development tool used for the production of the system ("MUSE") provides a "Blackboard Architecture". In this type of architecture, a problem is considered by a number of different "knowledge sources", each of which contain knowledge about particular aspects of the problem, or about particular behavioural rules or situations etc. Hypotheses or partial solutions are built up on the "blackboard" as each knowledge source makes its contribution. Each knowledge source monitors the development of the solution, and will act if it can contribute at any stage to further refinement.

Mixed mode reasoning is used in the rule bases: that is to say, forward and/or backward chaining can be applied as appropriate to developing a solution. In simple terms, a forward chaining process attempts to follow each set of consequences through to an end-point, which becomes its conclusion. Backward chaining sets up a hypothesis, and tests to see whether the conditions necessary to support that hypothesis are present, in which case it adopts the hypothesis as its conclusion, or part of its conclusion (else it may try another hypothesis).

The main types of knowledge which are invested in the system are in terms of fault pattern matching, and causal knowledge. Causal knowledge is the qualitative representation of physical, empirical and heuristic rules, which are used mostly in this system for confirmatory purposes.

The main means of extracting information for contributing to the stored knowledge was to use rule induction techniques on the experimental results as the basis for pattern definition and for generating matching rules. The aim of this approach was to establish and assess a means of automatically generating the knowledge base which can be used when installing the system on new and different types of engines. In practice, the output of the process still required some degree of expert refinement and qualification.

The test engines were run at several load/speed points firstly in a reference condition (immediately after overhaul) and then a large number of times having in each case one or more faults introduced, with varying degrees of severity. In each instance sets

of all the sensor readings were taken for analysis.

Each of the sensor readings were normalised and expressed in numerical but qualitative terms (0 to 3 representing normal up to high deviation, +ve for high, -ve for low). Natural variability and sensor accuracy both, of course, need to be taken into account. In this way a "deviation pattern" was described for each fault. Also, from this information, sensors could be graded according to their usefulness in different circumstances: as being not reactive at all to faults, or not reactive in a predictable or consistent way; as being very useful in detecting faulty conditions but not useful in discriminating between faults; or as being diagnostic of particular faults.

The basis of the fault diagnosis is the matching of the reading patterns derived from measurements taken during online operation in real time, against the deviation patterns stored from the above exercise. Subsequent estimation of condition is based on the patterns matched, the closeness of fit, and information from other knowledge sources which may be relevant.

It should be noted at this stage that the patterns upon which the condition diagnoses are based in the present system represent steady-state engine operation: that is to say, the effects of transient behaviour during manoeuvring, load changing etc. are not being considered at this stage. During on-line operation, therefore, the system will not attempt to diagnose while transient operation is detected. However, unlike the status monitoring equipments mentioned earlier, which must of course continue to operate at all times and under all conditions, condition monitoring need not be performed continuously, and there should be no problem in waiting for a suitable period of steady operation before performing the next assessment.

## 8. THE ROLE OF SIMULATION

Simulation is used in the system, in broad terms, to provide interpolation between the fixed points of knowledge. This is necessary in two areas.

Firstly, since the deviation patterns are to be compared with the reading patterns for the engine in reference condition, we need to know what the reference readings should be for the engine at the precise operating point at which the online readings have been taken. The experimental reference points (as described above) can only practically be taken at a small number of operating points. These points, therefore, are used to calibrate a model of the engine, and the readings for any point in the operating space of the engine can be generated by the model.

Since we are dealing here with a "reference" engine, the model needs only to represent a single behaviour, and we choose, for speed and efficiency reasons, to describe it mathematically via a "black box" model (using a polynomial). This gives a fast process which is also relatively easy to calibrate on-line, for example after a major maintenance or overhaul of the engine.

The other requirement for simulation in the system arises because the stored fault patterns represent a finite set of fault conditions, and precise matches are unlikely. Given a sufficiently accurate and flexible simulation, a fault hypothesis can be fed into it at given engine conditions, and it can predict a set of reading deviations which can then be matched against the measured set, to confirm or quantify the diagnosis. It can also be used to test for multiple-fault hypotheses; or to predict the behaviour of the engine at proposed operating points, with proposed fuels, or with supposed further degradation of components.

A simplified version of a thermodynamic simulation program has been adapted for the CPMPs system, allowing for online operation. Even this version is quite slow; although timescales of several minutes should not be prohibitive in this area of the system's functionality.

## 9. FUEL EFFECTS

Since the combustion performance of the engine is to be used in assessing its condition, then the effects on combustion of the particular type and quantity of fuel which is in use has to be taken into account.

In practice, different levels of information about those parameters of the fuel which affect its combustion properties might be available in different circumstances. The results of an on-shore laboratory analysis of the fuel are often obtained before a particular fuel is routed to the engine; the Chief Engineer may use an on-board "test kit" to yield some basic fuel properties; or as a minimum the density and viscosity of the fuel can be estimated from information on the bunker delivery ticket.

In order to obtain an assessment of fuel ignition/combustion characteristics, particularly when based on such variable or incomplete information, an expert system has been developed [Katsoulakos et al (2)]. This system is based on a Fuel Information Knowledge Base built up from expert knowledge, chemical and statistical analysis, and Rule Induction based on a large number of tests. The system will estimate, for a given set of fuel properties, a predicted range of Combustion Effect Parameters, as well as producing a broad characterization of the fuel, both in the

form of a report to the operator, and as an output to the predictive maintenance system (which will assess the effects of the particular fuel on the ageing rates of the engine components).

A set of measured Combustion Effect Parameters can be obtained from the results of the online monitoring of the engine (via heat release calculations based on the cylinder pressure diagram and ignition delay). These actual parameters are compared with the calculated parameters. Any discrepancy between the sets may be the result of an engine fault. Engine simulations run using both the predicted and calculated Combustion Effect Parameters will therefore be compared with the actual engine readings, and the results passed on to the Fault Diagnosis expert system to determine which set of parameters should be used to give the highest degree of confidence in assessing both the state of the fuel and of the engine.

#### 10. PERFORMANCE OPTIMIZATION

The function of the performance optimization system is to provide advice on the optimal engine settings given the assessed engine condition and fuel quality. It takes the form of an expert system which is being developed with the aim of minimizing fuel consumption and maximizing engine maintenance periods. In any given installation the options which can be taken under consideration will be limited by the adjustments which are actually available on the particular engine. On current installations these may include such parameters as charge air temperature, varying injection timing, varying injection flow rate, and variable geometry turbocharging.

#### 11. MAINTENANCE PLANNING

Maintenance activities generally can be classified in a number of ways, but fall broadly into those activities which are based on fixed or arbitrary maintenance schedules, and those which are reactive to the condition of the engine and its components. Cost savings can be achieved by adopting maintenance plans which are based on the measured or assessed condition of the engine [as demonstrated e.g. by Hind (3)]. This approach can also result in more efficient use of manpower, reductions in spares holdings, and increased engine availability and operating life.

Reactive maintenance planning is a complex subject with potentially a very large number of variable inputs. The baseline inputs are the planned or reference maintenance schedules for the engine components and subsystems, and the manufacturer's recommended maintenance periods, which will have been based on theoretical wear rates. These requirements will be modified by the effects of parameters which are being continuously assessed by the

Condition Monitoring system, in particular operation in faulty or "off spec" engine conditions, and operation with different qualities of fuel. Other dynamic effects which can potentially be monitored or manually input include operation in heavy weather conditions, and manual intervention for interim refurbishment.

Based on these parameters it is the aim of the Maintenance Planning expert system to produce short term (day-to-day), medium term (planned in-port maintenance), and long term (e.g. five-year) maintenance plans, which take into account statutory and Classification requirements.

In order to assess the short and medium term requirements, knowledge must be built into the system as to what activities can be done at sea and which must be done in port. In the case of a major engine condition degradation the alternative may present itself of continuing the voyage with the engine in its degraded state; or of stopping the engines for repair and then continuing with the engine in an improved state. The system will be capable of providing predictions of the performance in the degraded state and in the potential repaired state, allowing the appropriate choices to be made. In practice, the decision would have to take into account not only factors such as the length of the voyage, and the level of facilities available at the next port, but also financial factors (such as late delivery penalties), weather forecasts etc.

As the knowledge base is expanded to take into account more of these factors, advice of increasing quality can be presented to the ship's officers charged with making the ultimate decisions.

## 12 OPERATOR INTERFACE

One of the features of any expert system should be that it does not merely report a conclusion or hypothesis to the user, but is also able and prepared to justify its deductions. It must therefore record the route through which its logic passes, whether forward or backward chaining, so as to present, or to have available for presentation on request, the reasons for its choices at each decision point. In the general case this gives the operator greater confidence in the advice given, but it also allows the more experienced operator to question the system in the event that he is doubtful about the conclusions reached by it. He can, for example, force the system to temporarily ignore a sensor reading which he feels is doubtful but upon which the system has based a pivotal decision, so as to view what alternative conclusion might have been reached.

Whilst a textual format is appropriate for this kind of interaction between the system and the operator, it was considered

that the general situation display for the operator should be a relatively simple colour mimic picture. The one currently used shows the major subsystems of the engine as "blocks" on the display, one or more of which will change colour and show "FAULT" when a fault is diagnosed in that subsystem. "Selecting" the block brings up a diagrammatic representation of the subsystem, showing each of the sensors as having a "good", "suspect" or "failed" reading. Further information on each sensor (name, location, current reading) can then be summoned as required.

### 13 THE INTEGRATED SYSTEM

Although the first test phase has involved the use of the shore-based engine at Newcastle, it is the intention to move on to sea-trials very shortly afterwards. Therefore, whilst the development system used various workstations, DEC VAX computers and Personal Computers, the runtime system built up for the trials was chosen so as to reflect what might be a realistic configuration and physical format suitable for on-ship operation.

Figure 3 shows the online system configuration. The expert systems, which were all developed on a Sun Workstation, were ported onto a Motorola 68020-based processor system running on VME-bus. The simulator modules are also hosted on this processor. In order to perform the data acquisition, the operator interfacing, and most of the signal conditioning, an IBM PC-compatible 80286 processor board with Enhanced Graphics Adapter was added to the bus, sharing memory with the 68020.

The steady-state data is acquired using a Schlumberger system of serially-networked measurement pods (IMPs), which are mounted on the engine gantry and connected to the sensors. Each IMP is sealed and has high vibration and shock resistance. High-speed sensors are connected directly to Analogue-to-digital converter boards also mounted on the VMEbus.

In order to mount the processors, and also to provide a suitable operator input and display capability, an industrial workstation was chosen, as illustrated in figure 4. This unit has a sealed front panel, and also has a high shock and vibration specification. A shock-mounted removable disk allows engine data to be recorded regularly and removed for offline analysis. Operator input is via a sealed, membrane keyboard.



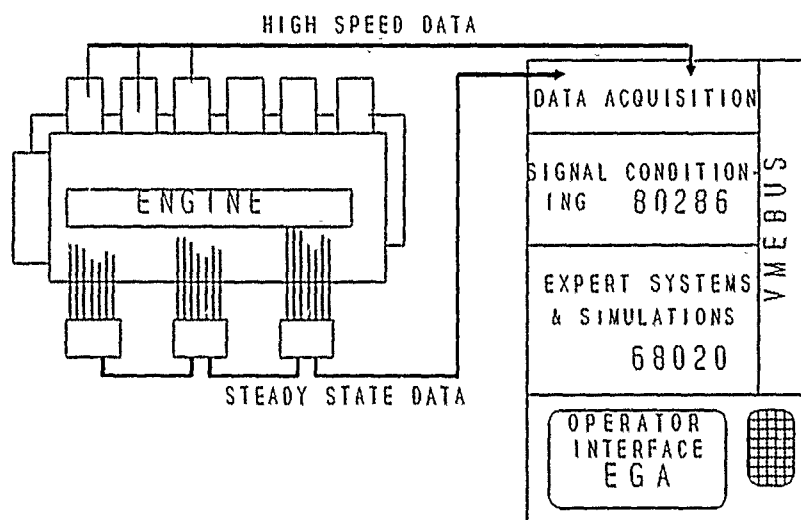


Figure 3: Schematic of Prototype Implementation

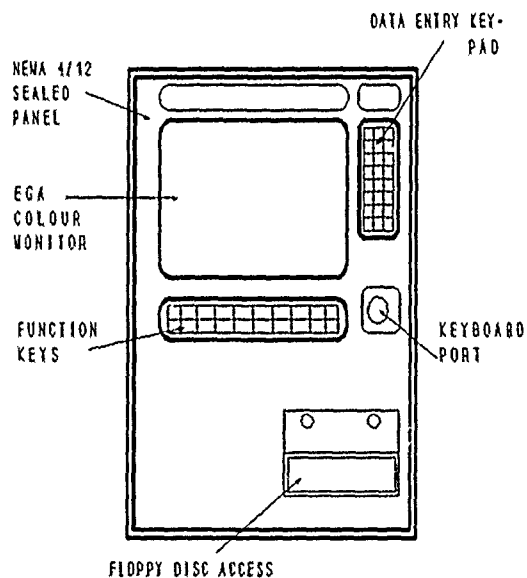


Figure 4: CPMPs Workstation

#### 14. SUMMARY AND CONCLUSIONS

The project has established the online use of expert system techniques, in conjunction with online engine simulations, to provide a means of continuously assessing the performance and condition of a marine diesel engine. Data to provide the knowledge bases has been derived using largely automatic means from experimental results - these relate to measurements of the engine's performance under various induced conditions, and the effect on the combustion characteristics of different types and quality of fuel. It has also been shown that the various functional subsystems can be adapted and integrated together into a processing unit of a size and type suitable for commercial "on board" use.

Further work on the system will investigate the degree of adaptation necessary to customise it onto any other type of diesel engine, and the level of automation which can be introduced into this process. A series of trials of the unit in a shipborne environment are also anticipated.

#### 15. ACKNOWLEDGEMENTS

The author would like to thank the U.K. Department of Trade and Industry for their support of the project, and wishes to acknowledge also the active participation of colleagues at the Marconi Company, Lloyd's Register of Shipping, and the other members of the Consortium. The author would also like to thank the Committee of the CPMPS project, and the Marconi Company for permission to publish this paper. Responsibility for all opinions in this paper rests with the author.

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## SPEED CONTROL OR FUEL CONTROL FOR MOTORSHIPS WITH FIXED PITCH PROPELLER

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### 1. ABSTRACT

There are 4 possible variables for the control of a fixed pitch propeller, driven by a diesel engine: speed of the ship, power to the propeller, revolutions of the propeller, and torque to the propeller, which is the same as fuel to the engine. The first two variables are rather impractical for various reasons, so there remain only two simple ways of controlling the main engine: revolution control and fuel control. The first method has the greatest similarity to the ship's speed control, the last one is better for the main engine load and somewhat simpler. Both systems are discussed in this paper.

### 2. GENERAL REMARKS

For liner ships but also sometimes for tramp ships there is the question for the optimum speed with the minimum fuel consumption to reach the next port in a predetermined time. This would not be a problem, when the ship would pass through an uniform sea (wind, waves, currents), because then the mean speed  $V_{SM} = s/\Delta t$  would be the lowest and therefore the best speed with the lowest fuel consumption for the voyage.

Unfortunately the ship encounters different sea states on its route and it might even change its draught and its trim during the sea voyage. For an optimization the sea conditions have to be known for the different parts of the voyage and for the time, when the ship will pass through these parts. This is nearly impossible. Who is able to predict sea and wind conditions in the southern Atlantic at the start of a voyage in Southampton, about 300 hours before the ship reaches the South Atlantic. So the skipper has to make an intelligent guess regarding the development of environment conditions for the different parts of the voyage (-here service experience is still asked for in the interpretation of global weather reports-) and he has to know the influence of wind, waves, draught and time on the resistance of his ship and on the propeller/propulsion efficiency. For the calculation of the fuel consumption per trip the mean specific fuel consumption of the main engine under service conditions with heavy fuel should be known also.

### 3. BASIC CALCULATIONS

Ship, propeller and main engine are matched at the design point, which is defined by the following values.

Displacement	$\nabla_0$
Draught	$T_0$
Trim	$T_{r0}$
Propeller power	$P_{p0}$
Propeller speed	$n_{p0}$
Ship's speed	$V_{s0}$
Ship's resistance	$R_{s0}$
Propeller efficiency	$\eta_{p0}$
Propulsion efficiency	$\eta_{D0}$
sea state: Wind	BF 0-1
sea	calm

With the following assumptions

$$\eta_{D0} / \eta_{p0} = \eta_{Dx} / \eta_{px} = \text{constant} \quad 3.1$$

$$R_{s0} / R_{sx} = (V_{s0} / V_{sx})^2 \quad 3.2$$

the energy per nautical mile becomes

$$p_{ox} = P_{px} / V_{sx} = p_{p0} (V_{sx} / V_{s0})^2 \quad 3.3$$

and the propeller power needed at design conditions at  $V_{sx}$  is

$$P_{px} = P_{p0} (V_{sx} / V_{s0})^3$$

$$P_{p0} = (R_{s0} \cdot V_{s0} / \eta_{D0})$$

$$R_{sx} = R_{s0} (V_{sx} / V_{s0})^2 \quad 3.4$$

Now the ship is very seldom sailing at design conditions. All deviations from these conditions have their influence on the resistance  $R_s$  and on the propeller efficiency  $\eta$ . The influence on the resistance is governed by equation 3.5.

$$\begin{aligned} R_{ssx} &= f \cdot f_{TR} \cdot f_{RS} \cdot f_E \cdot R_{sx} = f_{AS} \cdot R_{sx} \\ &= f_{AS} \cdot R_{s0} (V_{sx} / V_{s0})^2 \end{aligned} \quad 3.5$$

$$\begin{aligned} f_v &= (\nabla_x / \nabla_0)^{2/3} && \text{Displacement factor} \\ f_{TR} &= \text{Trim factor (To be defined for each ship individually)} \\ f_{RS} &= \text{Resistance increase due to heavy sea. (To be evaluated from voyage reports for each type ship)} \\ f_E &= 1 - 1,8 \text{ to } 2 && \text{Resistance increase due to hull fouling} \\ f_{AS} &= f_v \cdot f_{TR} \cdot f_{RS} \cdot f_E \end{aligned}$$

The power demanded by the propeller is then

$$\begin{aligned} P_{PSX} &= R_{SSX} \cdot V_{SSX} / (\eta_{DO} \cdot f_{ES}) = \\ &= f_{AS} \cdot R_{SOX} \cdot V_{SSX} / (\eta_{DO} \cdot f_{ES}) \\ &= f_{PS} \cdot P_{POX} \end{aligned} \quad 3.6$$

$$\begin{aligned} f_{ES} &= \eta_{OS} / \eta_{OO} = \eta_{DS} / \eta_{DO} && \text{Propeller efficiency factor} \\ f_{PS} &= f_{AS} / f_{PS} && \text{Propeller power factor} \end{aligned}$$

Ship resistance, ship's speed, propeller power and propeller speed are connected by the propeller free flow diagram (Fig. 1) with the following equations.

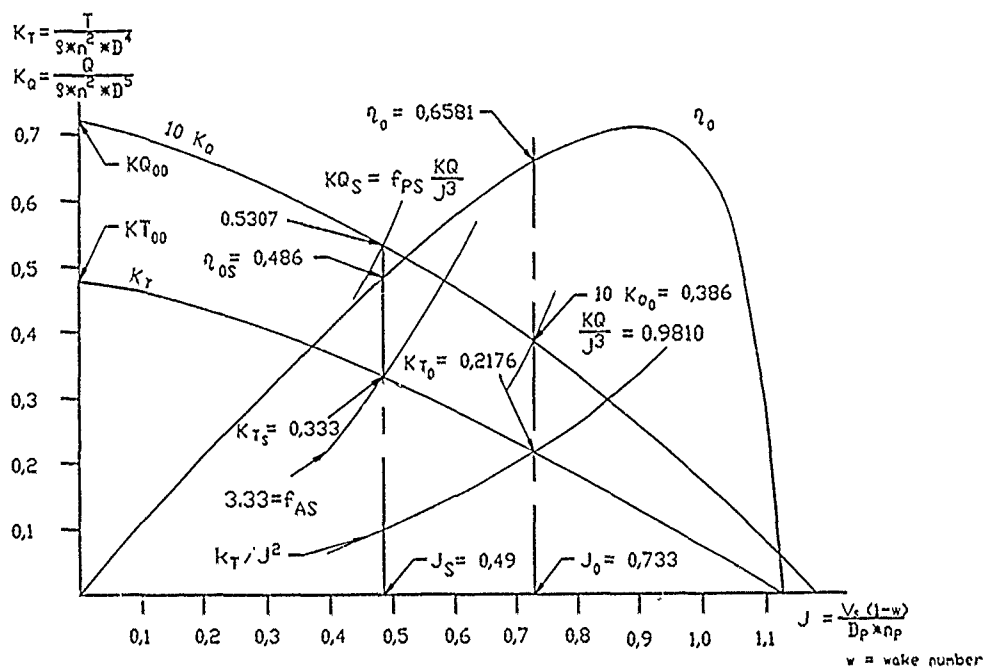


Fig. 1 propeller characteristics

$$\begin{aligned} R_S &= T (1 - t) \\ V_A &= V_S (1 - W) \\ J &= V_A / (n \cdot D_P) \end{aligned} \quad 3.7$$

$$\begin{aligned} f_{AS} &= (K_{TS}/J_S^2) / (K_{T0}/J_0^2) \\ &= K_{TS}/K_{T0} \cdot S^{1-2} \end{aligned} \quad 3.8$$

$$f_{fs} = KT_s/KT_o \cdot KQ_o/KQ_s \cdot J_s/J_o \quad 3.9$$

$$\begin{aligned} f_{ps} &= f_{As}/f_{Es} = KQ_s/KQ_o \cdot J_o^3/J_s^3 \\ &= KQ_s/KQ_o \cdot S'^{-3} \end{aligned} \quad 3.10$$

$$S' = (V_{ssx}/n_{psx}) \cdot (n_{rox}/V_{sox}) = J_s/J_o \quad 3.11$$

$$\begin{aligned} p_{psx}/p_{rox} &= P_{psx}/P_{rox} \cdot V_{sox}/V_{ssx} \\ &= KQ_s/KQ_o \cdot J_o/J_s \cdot n_{rox}/n_{psx} \end{aligned} \quad 3.12$$

$T$  = thrust                       $t$  = thrust deduction  
 $W$  = wake number               $V_A$  = advance speed  
 $J$  = advance number            $KT$  = thrust factor  
 $KQ$  = torque factor             $S'$  = slip factor

The speed  $V_s$  is the ship's speed through the water. In the event of some current  $V_c$ , the speed over ground is

$$V_{sog} = V_s + V_c \quad 3.13$$

From the propeller diagram one gets also the following equations

$$J_s = S' \cdot J_o \quad 3.14$$

$$\begin{aligned} KT_s &= KT_{oo} (1 - A \cdot J_s^B) \\ &= KT_{oo} (1 - A (S' \cdot J_o)^B) \end{aligned} \quad 3.15$$

$$\begin{aligned} KQ_s &= KQ_{oo} (1 - a \cdot J_s^b) \\ &= KQ_{oo} (1 - a (S' \cdot J_o)^b) \end{aligned} \quad 3.16$$

The above equations allow the calculation of different load conditions for the propeller, they allow also some kind of route-optimisation for the ship.

#### 4. CALCULATION OF AN OPTIMUM VOYAGE

For an optimum voyage the distance between two ports has to be covered in a preset time schedule with the fuel consumption as low as possible.

To be able to do this calculation the skipper has to know the state of his ship (draught, trim) and the state of the sea area, he wants to cross. This latter means that in spite of modern global weather reports he has to do some good guessing. He will get the lowest fuel consumption when he can run with the lowest possible engine power. But the power of a Diesel engine is not controlled. Usually the propeller speed  $n_{px}$  is controlled variable, sometimes the fuel supply = propeller torque is controlled. This means that the mates need an optimum value for either the propeller speed  $n_{px}$  or the fuel rack position  $f_x$ .

When we concentrate on these 2 control modes, then the equations 3.8 to 3.12 can be simplified.

#### 4.1 Propeller Speed Control

$$n_{psx} = n_{pox} = \text{constant} \quad 4.1$$

$$V_{ssx}/V_{sox} = J_s/J_o = S' \quad 4.2$$

$$P_{psx}/P_{pox} = KQ_s/KQ_o \quad 4.3$$

$$p_{psx}/p_{pox} = (KQ_s/KQ_o) \cdot (J_o/J_s) = (KQ_s/KQ_o) \cdot S'^{-1} \quad 4.4$$

Equations 3.8 to 3.10 are valid for both types of control

#### 4.2 Constant Fuel Supply

A constant fuel supply per stroke means a constant torque of the engine and therefore also of the propeller.

$$\begin{aligned} Q_{ox} = Q_{sx} &= KQ_o \quad n_{pox}^2 \cdot S \cdot D^4 \\ &= KQ_s \quad n_{psx}^2 \cdot S \cdot D^4 \end{aligned} \quad 4.5$$

$$n_{psx}/n_{pox} = (KQ_o/KQ_s)^{1/2} \quad 4.6$$

$$V_{ssx}/V_{sox} = (KQ_o/KQ_s)^{1/2} \cdot (J_s/J_o) = (KQ_o/KQ_s)^{1/2} \cdot S' \quad 4.7$$

$$P_{psx}/P_{pox} = (KQ_o/KQ_s)^{1/2} \quad 4.8$$

$$p_{psx}/p_{pox} = J_o/J_s = 1/S' \quad 4.9$$

$$S' = (V_{ssx}/V_{sox}) \cdot (n_{pox}/n_{psx}) \quad 4.10$$

#### 4.3 Specific Propeller Power-Speed Diagram

A diagram with the specific propeller power  $p_p$  as a function of the ship's speed  $V_s$  can be drawn now with the power factor  $f_{ps}$  as a parameter, indicating the influence of the changes of the resistance  $R_s$  and the propeller efficiency  $\eta_o$ .

In this diagram lines of constant propeller speed  $n_{po}$  and constant propeller torque  $f_o$  are drawn through the propeller design point 0 ( $P_{po}$ ,  $V_{so}$ ,  $R_{so}$ ,  $\eta_{po}$ ,  $n_{po}$ ). These lines are specific for each ship and its propeller, but the deviations between two different ships are rather small as can be seen in the diagram of fig. 2.

Curve CNZ:  $D_p = 7 \text{ m}$ ,  $n_{po} = 87 \text{ RPM}$ ,  $\eta_o = 0.6795$ ,  
 $V_{so} = 18.5 \text{ kn}$ , 4 blades ;

Curve NS:  $D_p = 6.3 \text{ m}$ ,  $n_{po} = 86.5 \text{ RPM}$ ,  $\eta_o = 0.6581$ ,  
 $V_{so} = 17.8 \text{ kn}$ , 6 blades





The factor  $f_{RS}$  is best gained from the evaluation of voyage reports from ships of a similar type and size. For a 1650 TEU Container ship the values of table 1 might give an indication of the range of  $f_{RS}$  (- = wind from astern, + = wind from  $\pm 30^\circ$ ).

Table 1 Resistance factor  $f_{RS}$  for head winds for a 1650 TEU Container Ship

BF	- (1-2)	+ (1-2)	3	4	5	6	7	8	8-9
$f_{RS}$	0,95	1,05	1,1	1,2	1,5	1,8	2,3	2,9	3,3

(These values are extrapolated from some log abstracts of different container ships of similar size. For ships with greatly different displacement they have to be seperately evaluated.)

It is now possible to calculate the overall resistance factor

$$f_{AS} = f_{VX} \cdot f_{RS} \cdot f_E \cdot f_{TR}$$

With  $f_{AS}$  and equ. 3.8 and 3.9  $S'$  and  $f_{ES}$  can be calculated and with these values the power factor  $f_{PS}$ . Fig. 3 shows the values for  $S'$  and  $f_{ES}$  as a function of the total resistance factor  $f_{AS}$  for our example ship with the following design data

$$P_{PO} = 7350 \text{ kW}, n_{PO} = 95,3 \text{ min}^{-1}, V_{SO} = 17,8 \text{ kn}, T_o = 9,7 \text{ m}$$

$$V_o = 29765 \text{ to}, f_o = 0,725, m_{DSPEC} = 0,184 \text{ kg HFO/kWh}$$

$$J_o = 0,7329, K_{T_o} = 0,2176, K_{Q_o} = 0,3851 \cdot 10^{-1}, \eta_o = 0,6581$$

The propeller slip  $S' = (V_{SSX}/n_{PSX}) / (V_{SO}/n_{PO})$  can be measured during the voyage of the ship. From these measurements the total resistance factor  $f_{AS}$  and the efficiency factor  $f_{ES}$  and the power factor  $f_{PS}$  can be calculated and a reference table for the ship can be built up easily.

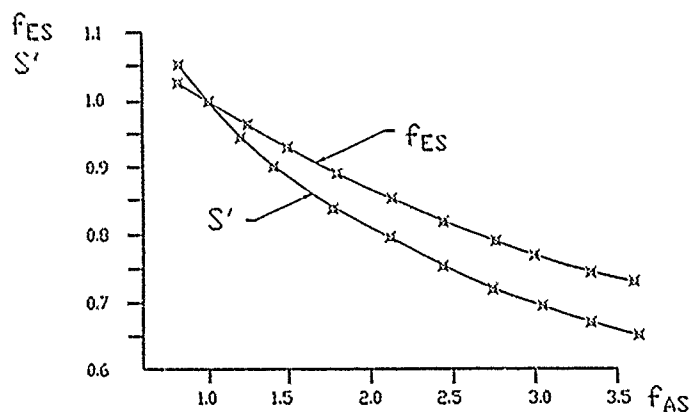


Fig. 3  $f_{ES}$  and  $S'$  as function of the overall resistance factor  $f_{AS}$

## 5. CALCULATION OF AN EXAMPLE

The ship has to sail from Karachi to Hongkong in 280 h in November. The route is divided into 3 parts (Fig.4).

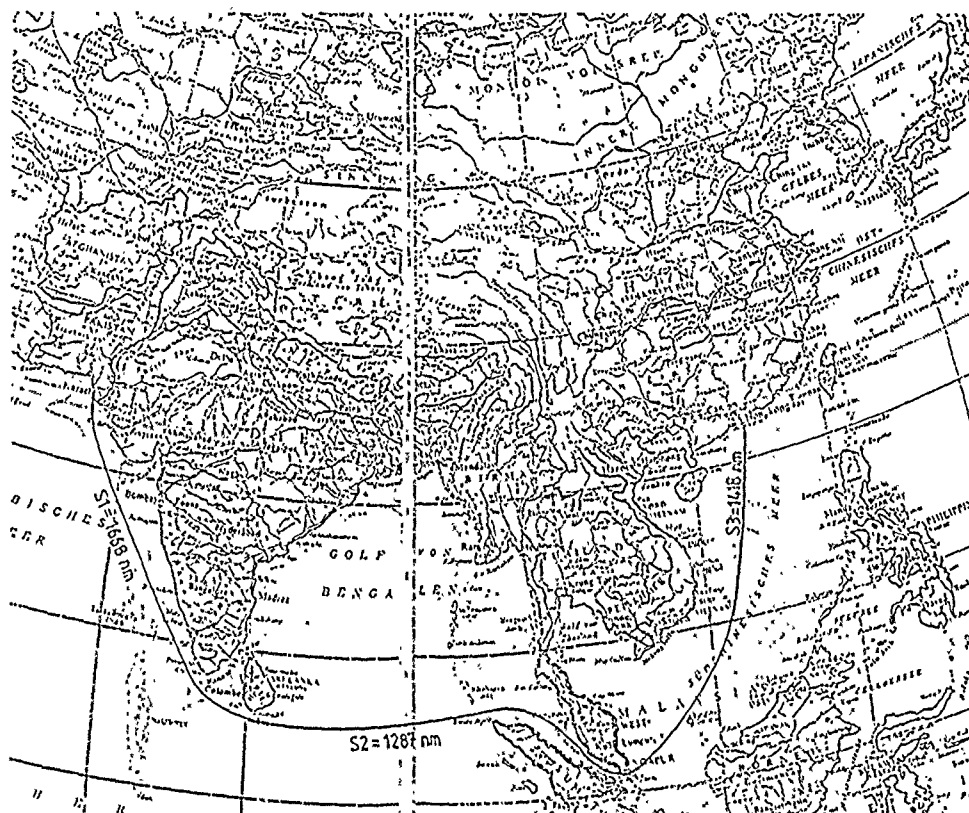


Fig. 4

S1 = 1668 nm Karachi - Southern tip of Sri Lanka  
 S2 = 1287 nm Sri Lanka Singapore  
 S3 = 1418 nm Singapore - Hongkong (Yellow Sea)  
 Σ S = 4737 nm

When the whole voyage has to be finished in  $t = 280$  h then the average speed should be  $V_{sm} = 15,62$  nm/h. The third part of the route is against a full NE-Monsoon with Beaufort 6 - 7 and the first leg is against a current of  $V_{cu} = -0,8$  kn. To show the difficulties of optimising a 280 hour voyage, the skipper has to consider, that on the third leg the Monsoon might develop into a Baby-Typhoon with winds going up to Bf. 8 - 9, so an average of 7 - 8 for S3 has to be considered too.

In table 2 the factors for the 3 voyage parts are evaluated.

Table 2. Evaluation of route factors  $f_{AS}$ ,  $f_{ES}$ ,  $f_{PS}$

part	length nm	$V_{icu}$ kn	wind Bf	draught m	trim m	$f_{RS}$	$f$	$f_{TR}$	$f_E$	$f_{AS}$	$f_{ES}$	$f_{PS}$
S1	1668	-0,8	-2	9,7	0	0,93	1	1	1	0,93	1,01	0,92
S2	1289	0	+3	9,7	0	1,1	1	1	1	1,1	0,985	1,12
S3	1418	0	+6,5	9,7	0	2,1	1	1	1	2,1	0,855	2,46
S3a			+7,5			2,55	1	1	1	2,55	0,808	3,16

In the propeller load diagram for this ship (Fig.5), the point 1 is put in with  $f_{PSM} = 1.5$  and  $V_{SM} = 15.62$  kn. Through this point lines of constant propeller speed  $n_{POX}$  and constant fuel stroke  $f_{OX}$  are drawn. They show  $V_{SOX}(n) = 17.3$  kn,  $n_{POX} = 93.3 \text{ min}^{-1}$ ,  $P_{POX} = 6747 \text{ kW}$  or  $f_{OX} = 0.765$ ,  $V_{SOX}(f) = 18.2$  kn,  $P_{POX} = 7935 \text{ kW}$ . Then the lines for  $f_{PS1}$ ,  $f_{PS2}$  and  $f_{PS3}$  are put into the diagram also. Now the first calculation for this voyage can be made. It is to be done for the propeller speed  $n_{POX} = 93.3 \text{ min}^{-1}$ . From the diagram the values  $V_{SSX1}$ ,  $P_{PSX1}$ ,  $V_{SSX2}$ ,  $P_{PSX2}$  and  $V_{SSX3}$ ,  $P_{PSX3}$  (points  $n_1$ ,  $n_2$ ,  $n_3$ ) are taken and evaluated in table 3.

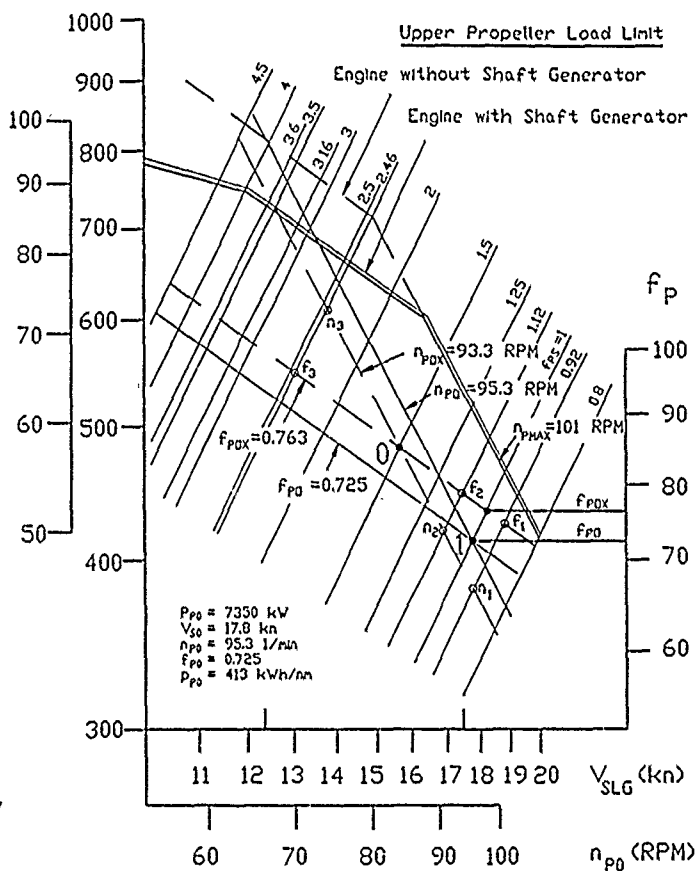


Fig. 5 Route optimising diagram for a 1650 TEU container ship

Table 3. Evaluation of voyage for  $n_{pox} = 93,3 \text{ min}^{-1}$ 

part -	V <sub>slc</sub> kn	V <sub>soc</sub> kn	t h	p <sub>psx</sub> kWh/nm	P <sub>psx</sub> kW	m <sub>b</sub> to	n <sub>psx</sub> min <sup>-1</sup>	m <sub>bs</sub> kg/nm	V <sub>slc</sub> = speed by log
S1	17,7	16,9	98,7	390	6903	125,4	93,3	75,2	V <sub>soc</sub> = speed over ground
S2	16,9	16,9	76,2	420	7098	99,5	93,3	77,3	
S3	13,8	13,8	102,8	612	8446	159,8	93,3	112,7	
			277,7			384,7		81,2	m <sub>bs</sub> = m <sub>b</sub> /S
S3a	13,5	13,5	105,1	590	7960	153,9	91,0	108,5	
			280,0			378,8		80,0	

It can be seen, that this simple approximation achieves already a result, which would not need another closer evaluation. The lowest fuel consumption is achieved, when on the third leg the propeller speed is reduced to  $91 \text{ min}^{-1}$  then only 378,8 to of heavy fuel are needed to bring the ship from Karachi to Hong-kong in 280 h. With constant fuel supply the calculation is shown in table 4 (points  $f_1$ ,  $f_2$  and  $f_3$  in Diagram 5).

Table 4. Evaluation of voyage for  $f_{ox} = 0,762$ 

part -	V <sub>slc</sub> kn	V <sub>soc</sub> kn	t h	p <sub>psx</sub> kWh/nm	P <sub>psx</sub> kW	m <sub>b</sub> to	f <sub>ox</sub> -	m <sub>bs</sub> kg/nm
S1	18,8	18,8	92,7	425	7990	136,3	0,765	81,7
S2	17,4	17,4	74,0	450	7830	106,6	0,765	82,8
S3	13,05	13,05	108,7	550	7178	143,6	0,765	101,3
			275,4			386,3		88,4
S3a	12,5	12,5	113,3	505	6313	131,6	0,725	92,8
			280,0			374,5		85,6

The result of the constant fuel supply calculation is also satisfactory, the voyage time is 4.6 h short with the first try. When the fuel supply is reduced to  $f_{oxa} = 0,725$  for the third leg, then the fuel consumption for the whole trip is  $m_b = 374,5$  to which is slightly less than with constant propeller speed.

If the captain discovers during the trip to Singapore, that beyond Singapore the wind is not Beaufort 6 - 7 but in the mean nearer to BF 8, then he has to increase his power if the ship can stand it - up to the maximum permissible engine power. With  $f_{ps3a} = 3,16$  this would be  $p_{psx} = 700 \text{ kWh/nm}$  and  $V_{ssx} = 13,1 \text{ kn}$ . The results can be seen in the next tables.

Table 5. Evaluation of voyage for  $n_{pox} = 93,3 \text{ m}^{-1}$  and  $f_{ps3a} = 3,16$ 

part -	V <sub>slc</sub> kn	V <sub>soc</sub> kn	t h	p <sub>psx</sub> kWh/nm	P <sub>psx</sub> kW	m <sub>b</sub> to	n <sub>pox</sub> min <sup>-1</sup>	f <sub>ox</sub> -	m <sub>bsr</sub> kg/nm	p <sub>psxr</sub> kWh/nm
S1	17,7	16,9	98,7	390	6903	125,4	93,3	0,68	75,2	408,5
S2	16,9	16,9	76,2	420	7098	99,5	93,3	0,71	77,3	420
S3	13,1	13,1	108,2	700	9170	182,6	94,0	0,925	128,8	700
			283,1			407,5			93,2	

Table 6. Evaluation of voyage for  $f_{OX} = 0,765$  and  $f_{PS3a} = 3,16$

part	VSLG kn	Vsog kn	t h	Ppsx kWh/nm	Ppsx kW	mb to	fsx -	nrox min <sup>-1</sup>	mps kg/nm	Ppsxr kWh/nm
S1	18,8	18,0	92,7	425	7990	136,3	0,765	98,5	81,7	444
S2	17,4	17,4	74,0	450	7830	106,6	0,765	95,5	82,8	450
S3	12,5	12,5	113,3	640	8000	166,8	0,84	90	117,6	640
			280,0			409,7			93,7	
S3a	12,2	12,2	115,3	610	7442	159	0,80	87,5	112,1	610
			282,3			401,9			91,9	

Both calculations show, that the skipper can barely meet his schedule, but in the case of propeller speed control he has to load his engine up to the limit and the mean speed of the ship is also rather high. In this case the fuel control mode fits the weather better as it increases the load  $f_x$  and the speed  $V_{sx}$  in areas of small power factors  $f_{PS}$ , so the engine (and propeller) load and the ships speed are smaller in the sea area with a high power factor  $f_{PS}$ .

Tables 2 - 6 show also the fuel consumption per nautical mile (by observation)

$$mbsi = m_{bi} / S_i$$

$$mbsm = m_b / S$$

The calculation can be checked by the real performance of the ship, when the momentary value of the fuel consumption of the ship is indicated on the video screen. In case of an activ shaft generator the measured fuel flow has to be corrected with the load ratio

$$mbsr = mbs \cdot P_{PX} / (P_{PX} + P_{EX} / \eta_G)$$

The propeller load factor  $p_{psx}$  is another indication, whether the voyage is going along the preplanned mode.

Figure 6 shows  $P_{psx}$  in function of the propeller speed in the engine load diagram. For control purposes  $P_{psx}$  from tables 5 and 6 are indicated in the diagram. With a good interpretation of the global weather reports the captain really can optimise his trip in regard to low fuel consumption and low engine load. The results of this final evaluation are shown in table 7.

Table 7. Final evaluation of voyage  $f_{ox} = \text{constant}$

part	VSLG kn	Vsog kn	t h	Ppsx kWh/nm	Ppsx kW	mb to	f <sub>ox</sub> -	npsx min <sup>-1</sup>	mps kg/nm
S1	18,9	18,1	92,2	435	8222	139,4	0,79	99,5	83,6
S2	17,7	17,7	72,7	455	8053	107,7	0,79	97	83,7
S3	12,0	12,0	118,2	593	7116	154,4	0,79	85,5	108,9
		15,45	283,1	499	7716	401,5			91,8

The fuel stroke setting of  $f_{0x} = 0,79$  would be the optimum for this trip and these load conditions. The real setting has to be corrected for the load of the shaft generator

$$f_{MX} = f_{0x} (1 + (P_{EXM} / \eta_G P_{PSXM})) = 0,84$$

$$m_{BR} = m_B (f_{MX} / f_{0x}) = 426,0 \text{ to}$$

for this trip.

## 6. COMPARISON OF SPEED CONTROL MODE WITH FUEL CONTROL MODE

The above calculations show that the power to the propeller has to be reduced by the mate, when the ship is running with propeller speed controlled into heavy weather. When the fuel supply to the main engine is controlled - this means a constant torque to the propeller shaft regardless of weather conditions. In this case the engine load has not to be adjusted when the ship is coming into a heavy weather area, because propeller and ship do adjust themselves to the weather conditions. Propeller speed  $n_{Px}$  and ship's speed  $V_{Sx}$  are reduced or increased according to the prevailing sea state - and without any control mechanism just by their characteristics. The fuel control mode is a clear case of a "Natural Control Characteristic". The fuel control mode is not restricted to the long sea voyages, it works also at short distances like Baltic Sea or North Sea. The automatic load restriction at all times brings not only a lower mean load of the engine but also quieter running conditions, as can be seen in the following figures. Fig. 9 shows the propeller speed  $n_{PSx}$  and the fuel rack position  $f_x$  as a function of the time in the upper part for speed control mode, in the lower part with constant fuel supply or fuel control mode. Fig. 10 shows a more detailed recording of the speed control mode. Here on can see that the controller - a standard Woodward governor - sometimes amplifies the revolution deviations. It can be stated, that the propeller speed deviations did not become greater, when the engine was run in the fuel control mode. Fig. 11 shows the engine load as a product of  $n_{Px} f_x$  for both tests. Here the better performance of the fuel control mode is so evident, that the figure does not need any discussion.

All calculations up to now were done for a single screw ship with one engine but they are valid also for ships with two propulsion systems. In this case the individual propeller delivers just half of the thrust  $T$  necessary to move the ship through the water with the speed  $V_{0x}$ .

With a twin screw ship running at design conditions with 79% of the design speed  $V_{S0}$  only 50% of the design propeller power  $P_{P0}$  is needed, but with  $P_{P0} = 0,75 P_{MCR}$  the actual engine load is  $P_{Px} = 0,375 P_{MCR}$ . If one engine is shut down - for maintenance or fuel saving - what power does the remaining service engine deliver to the propeller at what propeller speed to keep the ship's speed constant. The basic equations are regrouped for

$$W_{SSx} = V_{S0x} = \text{const.}$$

$$\frac{V_{SSx}}{V_{S0x}} = 1 = \frac{J_S}{J_0} \frac{n_{PSx}}{n_{P0x}} \quad 6.1$$

$$\frac{n_{PSX}}{n_{POX}} = \frac{J_0}{J_S} = \frac{1}{S'} \quad 6.2$$

$$\frac{P_{PSX}}{P_{POX}} = \frac{Q_{SX}}{Q_{SO}} \cdot \frac{n_{PSX}}{n_{POX}} = \frac{KQ_X}{KQ_0} \left( \frac{n_{PSX}}{n_{POX}} \right)^3 = \frac{KQ_X}{KQ_0} \cdot \left( \frac{J_0}{J_S} \right)^3 \quad 6.3$$

$$= \frac{P_{PSX}}{P_{POX}} = f_{PS}$$

$$\frac{f_X}{f_{OX}} = \frac{Q_{SX}}{Q_{SO}} = \frac{KQ_X}{KQ_0} \cdot \left( \frac{J_0}{J_S} \right)^2 \quad \begin{array}{l} \text{fuel rack position} \\ \text{= engine load} \end{array} \quad 6.4$$

$$f_{AS} = f_{RS} = \frac{KT_S}{J_S^2} \cdot \frac{J_0^2}{KT_0} = 2 \quad \begin{array}{l} \text{all thrust on} \\ \text{one propeller} \end{array} \quad 6.5$$

When our example propulsion system is considered as one plant of a twin plant system, then the calculations according to equ. 6.1 to 6.5 can be done with the following base values.

$P_{POX} = 3675 \text{ kW}$ ,  $V_{SOX} = 14 \text{ kn}$ ,  $n_{POX} = 75 \text{ min}^{-1}$ ,  $p_{POX} = 262,5 \text{ kWh/nm}$ ,  $f_{OX} = 0,459$

For  $f_{AS} = 2$  and for this propeller (Fig. 1) the calculation of the new load point gives the following results:

$$\begin{array}{lll} f_{PS} = 2,31 & P_{PAX} = 8490 \text{ kW}, & p_{PSX} = 606,5 \text{ kWh/nm} \\ S' = J_S/J_0 = 0,8086 & & n_{PSX} = 92,7 \text{ min}^{-1} \\ f_{OX2} = (P_{POX}/P_{PO})^{2/3} \cdot f_0 = 0,459 & & f_{SX} = 0,857 \end{array}$$

In fig. 6 and 7 these values are indicated with dashed lines. They show that at design state and fair weather one propeller needs 15.5% more power than two propellers would need together. Propeller load and engine load are well within their limitations.

If the change over would take place at rougher weather with  $B_f = 4,5$  and  $f_{PS} = 1,25$  and when the engines are run on speed control then the base figures are:

$V_{SSX} = 13,2 \text{ kn}$ ,  $p_{PSX2} = 286 \text{ kWh/nm}$ ,  $P_{PSX2} = 3789 \text{ kW}$ ,  $f_{SO2} = 0,49$ ,  $n_{POX} = 75 \text{ min}$

For one engine running alone with the same ship's speed they become:

$$P_{PSX1} = 660,5 \text{ kWh/nm}, \quad P_{PSX1} = 8690 \text{ kW}, \quad f_{SX1} = 0,91$$

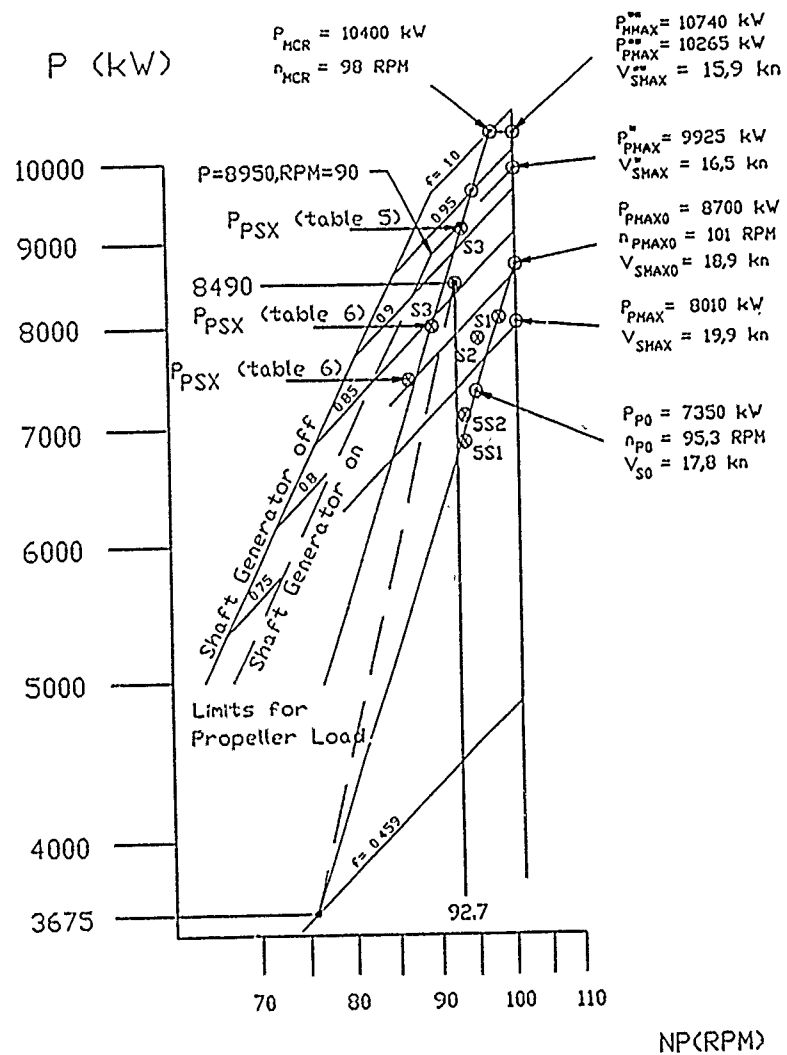


Fig. 6 Engine load diagram for a 1650 TEU container ship



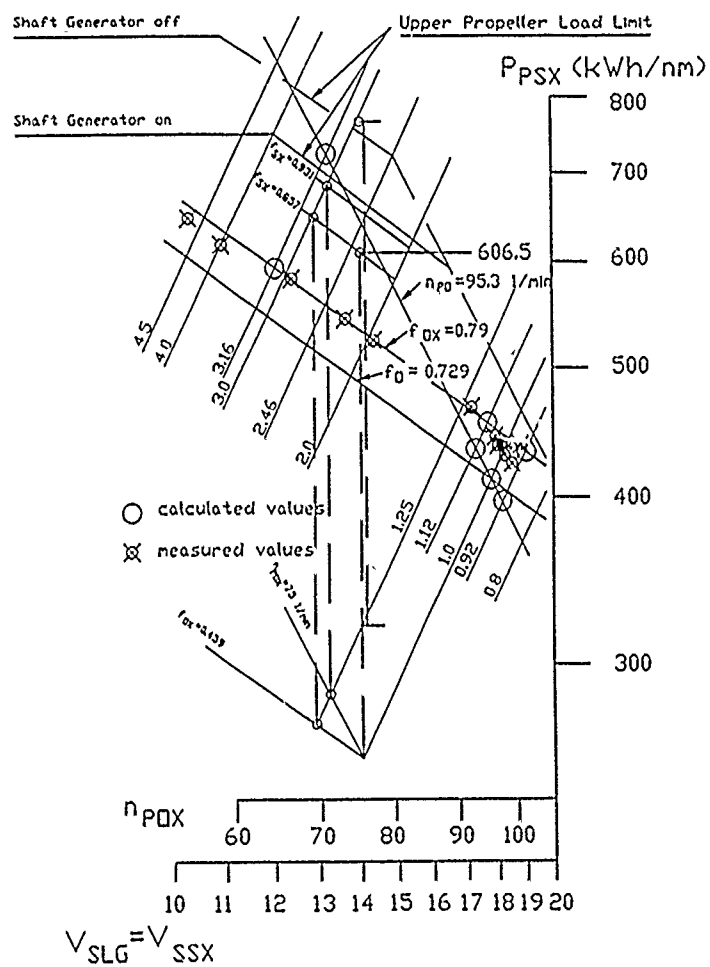


Fig. 7 Comparison of calculation and ship's data

Is the ship running in fuel control mode then the basic values are:

$V_{sx2} = 12,8 \text{ kn}$ ,  $P_{sx2} = 270 \text{ kWh/nm}$ ,  $P_{sx2} = 3456 \text{ kW}$ ,  $f_{sx2} = 0,459$ ,  
 $n_{sx2} = 73 \text{ min}^{-1}$

These become

$P_{sx1} = 624 \text{ kWh/nm}$ ,  $P_{sx1} = 7983 \text{ kW}$ ,  $f_{sx1} = 0,854$ ,  $n_{sx1} = 89,1 \text{ min}^{-1}$

Even with the rougher weather this engine stays within its limitations, which depends very much on the layout of engine and propeller. When the propulsion system is not properly designed for heavy weather conditions, then the engines are very often overloaded. In any case these examples also show, that the fuel control mode results in lower engine load but also in slightly less ship's speed.

## 7. CONCLUSIONS

In this paper the propeller speed control is compared with the engine fuel control. One result of the calculations is a simple method of route optimisation. It will achieve a low fuel consumption and a rather low engine setting. Some simple calculations - done with a pocket calculator - and a few parallel lines drawn into a diagram, are sufficient.

Naturally all the basic figures of the ship can be stored in a PC and the captain just feeds it with the basic data of the trip and of the displacement and the computers then calculate the optimum setting of the fuel rack or the propeller speed to achieve the optimum setting of the fuel stroke.

In Fig. 7 the calculated values from table 7 are indicated, also the daily records of a trip from Karachi to Hongkong (24.11. - 16.12.1987) (Fig. 8). Fig. 7 shows, that the optimum fuel rack setting was practically followed by the ship and it is therefore not astonishing, that the ship used practically the same amount of fuel as shown in table 7.

So this paper is only publishing the theories of a simple optimising system. Similar systems are already used on ships with obviously good results since their commissioning in 1985.

The second result is that the engine load will be the lowest, when only the fuel supply to the engine is controlled. Also a smoother running of the engine will be achieved. In addition to these two points, the ship-propeller-engine system is adjusting itself automatically to heavy weather conditions thus avoiding overload of the engine.

## LITERATURE

H.-H. Kirschnick, Technische Universität Berlin, W-Germany,  
Verbesserungen am Brennstoffsystem

## NORASIA LINE

R	C	D	E	F	G	H	I	J	K	L
SUPPLIED	CONSUMED DURING PORTSTAY	ON HAND STARTING	ON HAND START SEAVOYAGE	CONSUMED ON RIVER 1	ON HAND END SEAVOYAGE	ON HAND ARRIVAL	CONSUMED ON RIVER 2	CONSUMED DURING SEAVOYAGE	CONSUMED RIVER 1 + 2	TOTAL CONSUMED
	1338.4			F.O.D.E	H.O.A.C	H.O.H	H.E.G	K.H.H	L.O.H	
	1257.0	1125.4	0.5	630.2	619.0	7.2	436.3	3.7	321.0	
	7.2	119.0	313.4	0.2	113.4		-	0.4	2.7	
			XXX	XXX	XXX		XXX	XXX		
XXX	XXX			XXX			XXX	XXX	XXX	XXX

(1) S.S./M.S. M/V "Norasia Samantho"  
 (2) Date of Trip 1954  
 (3) Port of Origin Kuala Lumpur  
 (4) Port of Destination Singapore  
 (5) Date of Departure 15  
 (6) Date of Arrival 15  
 (7) Name of Ship M/V  
 (8) Name of Captain S. S. S.  
 (9) Name of Engineer S. S. S.  
 (10) Name of Pilot S. S. S.  
 (11) Name of Steward S. S. S.  
 (12) Name of Cook S. S. S.  
 (13) Name of Cabin Boy S. S. S.  
 (14) Name of Deck Hand S. S. S.  
 (15) Name of Radio Operator S. S. S.  
 (16) Name of Telegrapher S. S. S.  
 (17) Name of Interpreter S. S. S.  
 (18) Name of Surgeon S. S. S.  
 (19) Name of Pharmacist S. S. S.  
 (20) Name of Nurse S. S. S.  
 (21) Name of Doctor S. S. S.  
 (22) Name of Dentist S. S. S.  
 (23) Name of Optician S. S. S.  
 (24) Name of Barber S. S. S.  
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 (28) Name of Carpenter S. S. S.  
 (29) Name of Painter S. S. S.  
 (30) Name of Electrician S. S. S.  
 (31) Name of Plumber S. S. S.  
 (32) Name of Fitter S. S. S.  
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 (38) Name of Modelmaker S. S. S.  
 (39) Name of Draftsman S. S. S.  
 (40) Name of Surveyor S. S. S.  
 (41) Name of Engineer S. S. S.  
 (42) Name of Architect S. S. S.  
 (43) Name of Designer S. S. S.  
 (44) Name of Artist S. S. S.  
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 (115) Name of Stationery Importer S. S. S.  
 (116) Name of Stationery Exporter S. S. S.

Fig. 8

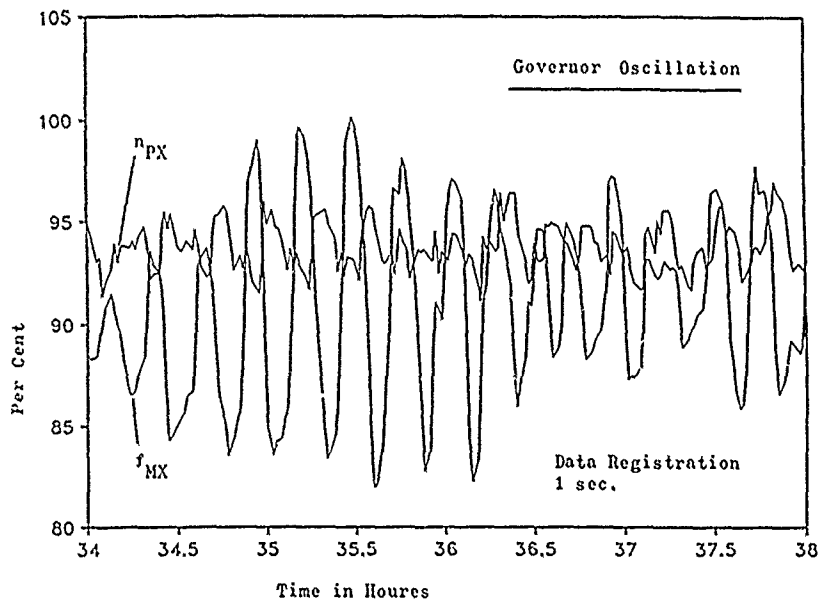


Fig. 10 Detailed Data Registration

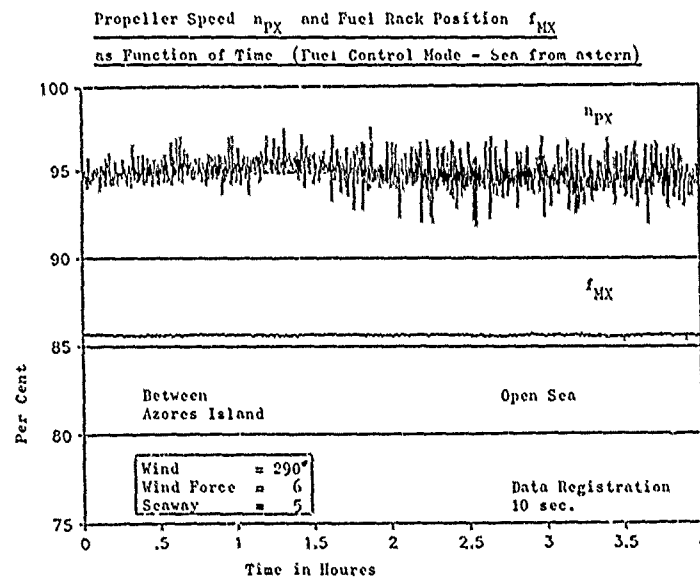
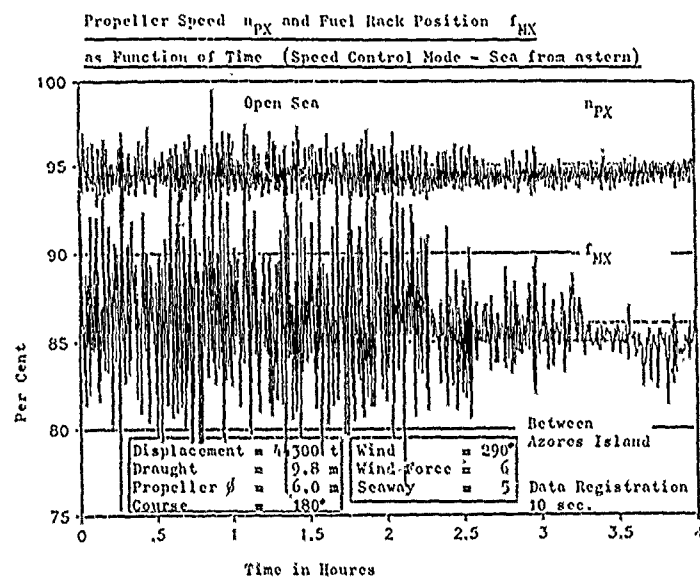
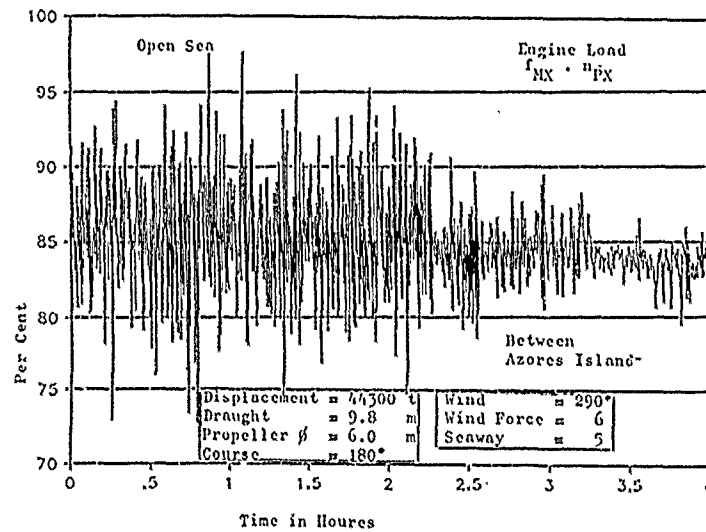


Fig. 9

Engine Load as Function of Time  
(Speed Control Mode - Sea from astern)



Engine Load as Function of Time  
(Fuel Control Mode - Sea from astern)

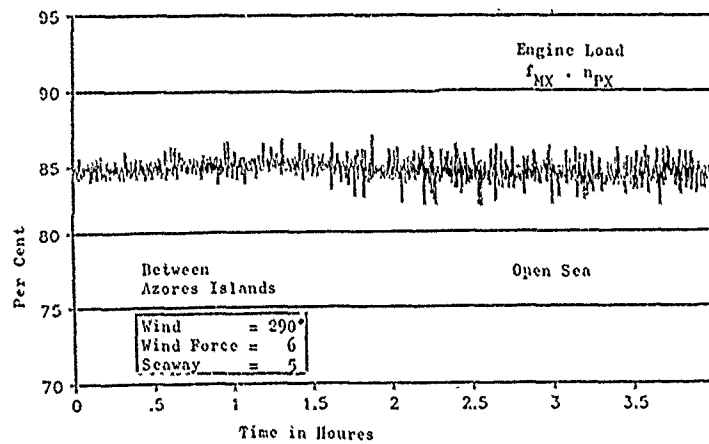


Fig. 11

## **A STATE-SPACE METHOD FOR RAPID SIMULATION OF PIECE-WISE LINEAR SYSTEMS**

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### **1. ABSTRACT**

A general method for the digital-computer simulation of piece-wise linear models of nonlinear and variable-structure 'switching' systems characterizing the fields of modern control and power electronics is based on the zero-input response of augmented state-space models of the constituent linear subsystems. The novel feature of the method, which greatly extends its range of convenient applicability, is the introduction of auxiliary variables proportional to the state, called decision vectors, and discrete logic (Boolean) vectors defined by the polarity of the components of these vectors, which together combine to govern the transition of the system state from one subsystem to the appropriate next one. Selected examples illustrate the versatility of the method.

### **2. INTRODUCTION**

While surveying the techniques available for rapidly computing the time-domain response of power-electronics and relay-type control systems, characteristic of the class of piece-wise linear systems, it appeared that there was no widely-applicable method for modelling the behaviour of such systems which took full advantage of linear state-space analysis principles. Instead, each new problem had to be solved from the beginning, without much recognition of an underlying common framework. The method to be described permits the complete (transient and steady-state) simulation of such systems as: converters, cycloconverters, inverters, choppers, switching power supplies, relay and saturating control systems, electric drives; in short, any system which can be described by one or more sets of linear ordinary differential equations with constant coefficients.

Accordingly, we write a set of first-order linear differential equations describing the state of each linear subsystem. Within each subsystem we introduce a linear combination of the

state components, called a 'decision' vector, whose polarity is checked at each time step in the solution. When one (or more) component(s) of the decision vector pass(es) through zero, the state moves to the designated next subsystem. Associated with the continuous decision vector is a discrete (0/1) Boolean vector and a Boolean 'mask' matrix to select the next active subsystem. It is these novel latter features which give this simulation method its power and flexibility.

The input function(s) driving the system may quite often be represented as the solution(s) of linear ordinary differential equation(s) [1, 2]. By augmenting the model state vector to include the input, the computer need only solve an initial-condition problem. Because each subsystem is linear, its transition matrix may be precomputed for the time-step size for which the output is desired [3, 4]. While the augmented (sub)system matrix has higher dimension than does the driven system, the need to numerically convolve the transition matrix with the input vector greatly reduces solution computation time. The time of transition from one subsystem to another is found more or less precisely by interpolation between time steps (a few Newton-Raphson iterations suffice). We assume the state to be continuous during the transition between subsystems; consequently, the 'initial' state in the new subsystem is the 'final' state in the preceding one.

Abrupt changes in state are caused by impulses in the input vector; their influence may be modelled by means of 'switch' matrixes [5]. Similarly, interval transformations [6] may be introduced to eliminate otherwise redundant state components which may arise in some subsystems. If the simulation programme caters for impulses, then it becomes capable of solving systems containing sample/hold elements [5]. The occurrence of an impulse does not necessarily invoke a new subsystem. State-dependent sampling could also be accommodated without further extension to the model.

Following development of the simulation model, we describe a computer programme for solving it; we conclude with some example illustrations from the fields of power electronics and automatic control.

## 2. MODEL DEVELOPMENT

We specify the state of a linear time-invariant subsystem by the following set of first-order differential equations:

$$\tilde{L} \dot{\tilde{x}} + \tilde{R} \tilde{x} + B u = 0; \tilde{x}(0) = \tilde{x}_0, \quad (1)$$

where  $\tilde{x}$  is an  $n$ -vector representing state, having initial value  $\tilde{x}_0$ ;  $\tilde{L}$  is an  $(n \times n)$  array of state-derivative multiplier coeffi-

cients;  $\tilde{R}$  is an  $(n \times n)$  array of state multiplier coefficients;  $u$  is an  $m$ -vector of forcing functions whose influence is defined by the  $(n \times m)$  control matrix  $B$ . The desired outputs, represented by the  $l$ -vector  $y$ , may be written:

$$y = \tilde{G} \tilde{x} + \tilde{H} \dot{\tilde{x}} + J u, \quad (2)$$

where  $\tilde{G}$ ,  $\tilde{H}$ ,  $J$  represent the contributions of the state, state derivative and input, respectively. Equations 1 and 2 are preferred for modelling electric circuits, particularly those containing mutual inductance.

In most cases of interest, the driving function  $u$  is deterministic, and may be computed as the solution of a set of linear ordinary differential equations with constant coefficients;  $u$  may then be given a state-space representation [1] which enables the system and its inputs to be modelled as a larger system, but now having zero input. The resulting initial-condition response may be accurately and rapidly computed [3]. A linear combination  $Q$  of the solutions of Eq 3 provides the forcing function  $u$ ; i. e.,

$$I \dot{w} + P w = 0; w(0) = w_0; \quad (3)$$

$$u = Q w, \quad (4)$$

where  $I$  is a suitable identity matrix. Substituting in Eqs 1 and 2, we obtain the (undriven) system described by Eqs 5 and 6:

$$L \dot{x} + R x = 0, x(0) = x_0; \quad (5)$$

$$y = G x + H \dot{x}, \quad (6)$$

where augmented state vector and system matrixes are defined by:

$$x = \begin{bmatrix} \tilde{x} \\ w \end{bmatrix}, L = \begin{bmatrix} \tilde{L} & 0 \\ 0 & I \end{bmatrix}, R = \begin{bmatrix} \tilde{R} & BQ \\ 0 & P \end{bmatrix}, G = \begin{bmatrix} \tilde{G} & JQ \end{bmatrix}, H = \begin{bmatrix} \tilde{H} & 0 \end{bmatrix}. \quad (7)$$

For sake of model completeness, in those situations where short-duration pulses present in the input may be represented as impulses, we may write:

$$u(t) = u_c(t) \delta(t-t_0), \quad (8)$$



where  $\delta(t-t_0)$  is an impulse occurring at  $t = t_0$ , and  $u_c$  is continuous at  $t = t_0$ . Substitute for  $u$  in Eq 1 and integrate over the short interval  $t_0^- < t < t_0^+$ ; then the state after the impulse becomes

$$x(t_0^+) = x(t_0^-) - L^{-1} B u_c(t_0). \quad (9)$$

When  $u_c$  is generated by Eqs 3 and 4, the state of the system following an impulse at  $t_0$  is

$$x(t_0^+) = S x(t_0^-), \quad (10)$$

$$\text{where } S = \begin{bmatrix} I & -L^{-1}BQ \\ 0 & I \end{bmatrix}; \quad (11)$$

$S$  is a switch matrix. In the absence of impulses,  $S = I$ ; the state is then continuous at  $t_0$  [5].

Sample-hold elements may readily be included in piece-wise linear system models through application of the switch-matrix concept. In Eq 3, partition  $w$  and  $P$  into

$$w = \begin{bmatrix} w_h \\ w_c \end{bmatrix}, \quad P = \begin{bmatrix} P_h & 0 \\ 0 & P_c \end{bmatrix}, \quad (12)$$

respectively.  $P_h$  accounts for the hold-element dynamics of  $w_h$ , while  $P_c$  represents the continuous-time component  $w_c$ . At sample instants  $t_m$ ,  $m = 0, 1, 2, \dots$ ,

$$w(t_m^+) = S w(t_m^-); \quad (13)$$

$$S = \begin{bmatrix} 0 & S_h \\ 0 & I_h \end{bmatrix} \quad (14)$$

is the switch matrix for the sample-hold operation.

Arrays  $L$ ,  $R$ ,  $G$ ,  $H$ , and any switch matrixes  $S$  required, along with others ( $E$ ,  $F$ ,  $M$ ,  $s$ ) to be associated with the decision and next-subsystem selection processes, comprise the data to be input to the computer for each subsystem.

It is possible that state components which are independent in one subsystem will not be so in another. Rather than reduce the dimension of the state space in such instances, we may compute these 'redundant' states and output their difference as a check on model correctness and computational accuracy. Interval transformations are not required.

Equations 5 are manipulated by the computer into the 'standard' state-space form for solution:

$$\dot{x} = A x, x(0) = x_0; \quad (15)$$

$$y = C x, \text{ where} \quad (16)$$

$$A = -L^{-1}R, \quad C = G + HA. \quad (17)$$

In general, each subsystem is described by different A and C matrixes.

For any linear subsystem, the solution of Eq 15 is

$$x(t) = \exp(At) x_0. \quad (18)$$

For uniform time steps of duration T,  $t = k T$ ,  $k = 0, 1, \dots, K$ , Eq 18 becomes

$$x(kT) = \exp(AkT)x_0 = [\exp(AT)]^k x_0; \text{ i. e.,} \quad (19)$$

$$x(kT) = \phi(T)x((k-1)T), \quad (20)$$

where  $\phi(T) = \exp(AT)$ .  $\phi(T)$  is the (sub)system transition matrix; it may be precomputed for all subsystems by a fast algorithm [4]. Equation 20 is a recursion formula for the rapid calculation of x.

From Eqs 16 and 20, output vector y is given by

$$y(kT) = C x(kT). \quad (21)$$

**2.1 Decision and Change** The solution of the state equations (Eqs 15, 20) for a particular subsystem is carried out at uniform time instants. The decision to invoke a new subsystem is based on the polarity (sign) of one or more components of a 'decision' vector  $d(t)$ , of length  $i_1$ , comprising a linear combination of the compo-

nents of  $x(t)$ . Decision vector  $d$  has the form

$$d = E x + F \dot{x} = D x, \quad (22)$$

where  $D = E + FA$  is computed from input  $(i_1 \times n)$  coefficient matrixes  $E$  and  $F$ .

Associate with  $d(t)$  a Boolean polarity vector  $p$  such that  $p_i = 0$  if  $d_i$  is  $\geq 0$ , and  $p_i = 1$  if  $d_i < 0$ ;  $i = 1, 2, \dots, i_1$ . Associate with the  $h_1$  - vector  $s$ , being a list of possible next subsystems, a Boolean vector  $q$  of length  $h_1$  such that  $q_h = 1$  if the required combination of components of  $p$  is 1; i. e.,

$$s = [s_1 \ s_2 \ \dots \ s_{h_1}]^T, \quad (23)$$

$$q = M \& p, \quad (24)$$

where  $M$  is an  $h_1 \times i_1$  Boolean mask matrix whose elements are either 0 or 1.  $M_{hi} = 1$  indicates those elements of  $d_i$  which are instrumental in selecting subsystem  $s_h$ .  $\&$  represents the logical AND operation involving only those elements of  $p$  for which  $M_{hi} = 1$ . If more than one combination (logical OR) of components of  $d$  can lead to the same next subsystem, that subsystem number would appear more than once in  $s$ .

At each time step,  $d$  and  $p$  are computed. If no component of  $p$  is 1, no change of subsystem is required and the output  $y$  is computed. If one or more components of  $p$  is 1,  $q$  is computed from Eq 24. If all components of  $q$  are 0, the state continues in the present subsystem. In view of this, when one or more components of  $q$  is 1, there is a minimum-length essential subset  $p_e$  of components of  $p$  which must also be 1.  $p_e$  is given by

$$p_e = M^T \& q = M^T \& M \& p; \quad (25)$$

the number of 1's in  $p_e$  is never more than the number of 1's in  $p$ .

$$\text{For example, let } p = [1 \ 0 \ 1]^T, \text{ and } M = \begin{bmatrix} 1 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix};$$

then  $p_e = [0 \ 0 \ 1]^T$ , using Eq 25.

We must, in general, interpolate between two adjacent time

instants to determine the precise time to invoke a new subsystem; the following considerations apply.

For each  $h$  for which  $q_h = 1$ , the corresponding subscripts  $i$  for which  $p_{ei} = 1$  are stored during the computation in Eq 25. The component  $d_i$  of  $d$  associated with  $p_{ei}$  which goes negative at the latest time controls the transition of  $q_h$  from 0 to 1; call this time  $t_{maxh}$ . When several values of  $t_{maxh}$  occur (i. e., whenever more than one component of  $q$  is 1),  $h_0$ , the subscript associated with  $t_{min}$ , the earliest of the set of latest times, determines the next subsystem; we write

$$t_{min} = \min_h \{t_{maxh}\}, \quad (26)$$

$$next = s_{h_0}. \quad (27)$$

For the example situation illustrated in Fig 1,  $d_1, d_2, d_3$  become negative at times  $t_1, t_2, t_3$  respectively. At  $t = (k+1)T$ ,  $p = [1 \ 1 \ 1]^T$ . For

$$M = \begin{bmatrix} 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}, \quad p_e = p, \quad t_{max1} = t_3, \quad t_{max2} = t_2. \quad \text{Then, from Eqs 26}$$

and 27,  $t_{min} = t_2$  and  $h_0 = 2$ ; hence,  $next = s_2$ .

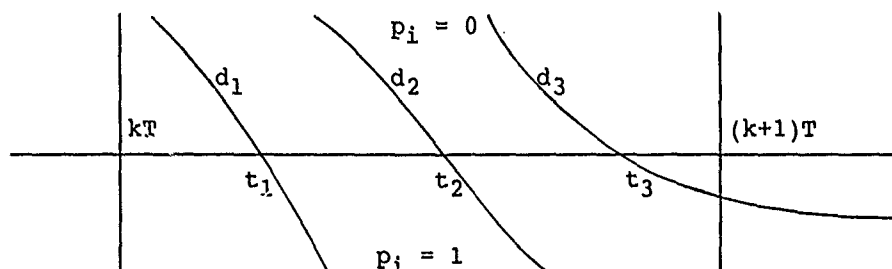


Fig 1. Determination of  $t_{min}$  and Selection of Next Subsystem.

The times of transition of the relevant components of  $d$  through zero are found by interpolation using a Newton-Raphson technique [7]. The time required to compute  $t_{min}$  is smaller if the number of 1's in  $p_e$  is less than the number of 1's in  $p$ ; this justifies the introduction of  $p_e$  and its calculation.

Now, we have found  $t_{min}$  more or less precisely, along with the next subsystem to which the state moves. Because the state

at  $t_{\min}$  is continuous, the 'initial' state in the new subsystem is also the 'final' state in the old one; thus,

$$x_{\text{new}}(t_{\min}) = x_{\text{old}}(t_{\min}) = x(t_{\min}) ; \quad (28a)$$

$$y_{\text{new}}(t_{\min}) = C_{\text{new}} x(t_{\min}); \quad (28b)$$

$$d_{\text{new}}(t_{\min}) = \bar{D}_{\text{new}} x(t_{\min}). \quad (28c)$$

A step of less than  $T$  seconds is required to bring the time base to an integral multiple of  $T$  after a subsystem change takes place; hence,

$$x((k+1)T) = \phi((k+1)T - t_{\min}) x_{\text{new}}(t_{\min}). \quad (29)$$

### 3. COMPUTER PROGRAMME DESCRIPTION

A computer programme implementing most of the modelling concepts described above (impulsive inputs and sample/hold capability are not fully incorporated) was written in Microsoft Fortran v5.0 for a 12 MHz IBM PC/AT-type computer with a mathematics coprocessor. The operations indicated in the flow diagram of Fig 2 are executed by one or more subprograms. Each two-dimensional array has, in effect, a third dimension associated with it: namely, subsystem number. All arrays are manipulated as single-subscript (vector) quantities [8].

Arrays  $L, R, G, H, E, F, M, s$  are input sequentially, for  $NS$  subsystems, from keyboard or file. Matrixes  $A, C, D$  are then computed. Once time step  $T$  has been input, constant transition matrixes  $\phi$  are calculated and stored for sequential computation of the state. Starting state  $x_0$ , initial subsystem number  $j_0$ , time step  $T$  and final time  $TF$  are input anew for each solution 'run'.

State  $x$  is computed for  $K$  uniform time steps of duration  $T$ , and at each transition to a new subsystem. At these times, subsystem number and output are stored for later processing.

Following computation of  $x_{k+1}$ , decision vector  $d$  and polarity vector  $p$  are computed. If  $p = 0$ , the state continues in the present subsystem; time-step number  $k$  is incremented by 1 and output  $y$  is computed and stored. If  $p \neq 0$ ,  $q$  is computed; if  $q = 0$ ,  $k$  is again incremented by 1, and  $y$  is computed and stored, and the state remains in the present subsystem. If any component  $q_h$  of  $q$  is 1, the relevant components of  $d$  are solved for the earliest time  $t_{\min}$  of their transition through zero which caused  $q_h$  to change from 0 to 1, as described in Sec 2.1. Output  $y(t_{\min})$  is stored. Note that  $y$  need not be continuous at  $t_{\min}$ . The transition matrix  $\phi$  is computed for the remaining partial time step,

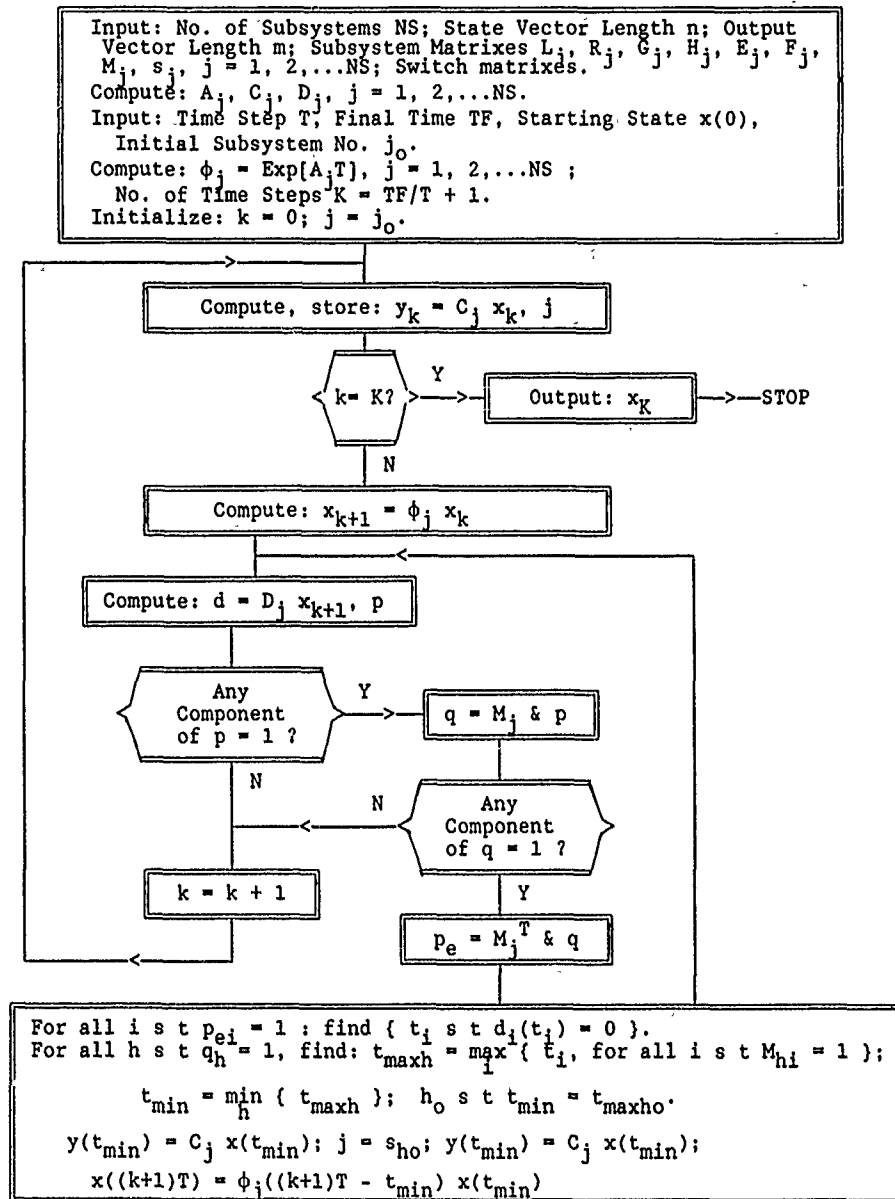


Fig 2. Computation Flow Diagram.

and, from it, state  $x_{k+1}$ . The process returns to the main stream, with computation of  $d$  and  $p$ .

#### 4. ILLUSTRATIVE EXAMPLES

Two examples, selected from the area of electric drive systems, are presented to demonstrate the capabilities of the simulation method described above. For each, we start with a circuit or block diagram; from it, we define linear subsystems and assign state variables, output and decision vectors. Graphs of typical responses, computed for selected numerical parameters, complete each example.

**Example 1. Electric Drive Transient Response.** Two identical superconducting motors, each driving a propeller shaft under steady-state conditions, and having different power-supply circuit impedances, experience a sudden drop in supply voltage. We wish to determine the subsequent motor currents, shaft speeds and load voltage. With reference to Fig 3, and, assuming 'ideal' components, we write the following model equations:

$$\begin{aligned}(L_1 + L_3)di_1/dt + L_3di_2/dt + (R_1 + R_3)i_1 + R_3i_2 + e_1 - e &= 0; \\ L_3di_1/dt + (L_2 + L_3)di_2/dt + R_3i_1 + (R_2 + R_3)i_2 + e_2 - e &= 0; \\ J_1dw_1/dt + B_1w - k_1i_1 &= 0; \quad J_2dw_2/dt + B_2dw_2/dt - k_2i_2 = 0; \\ de/dt = 0; e(0) = E; \quad e_1 = k_1w_1; \quad e_2 = k_2w_2; \quad i_3 = i_1 + i_2 \geq 0. \\ v = L_2di_2/dt + R_2i_2 + e_2. \quad (n \text{ is shaft speed in rev/min; } n = k_3w). \\ \text{Assign states: } x = [i_1 \quad i_2 \quad w_1 \quad w_2 \quad e]; \\ \text{let output } y = [i_3 \quad v \quad i_2 \quad n_1 \quad n_2]; \quad k_3 = 30./\pi.\end{aligned}$$

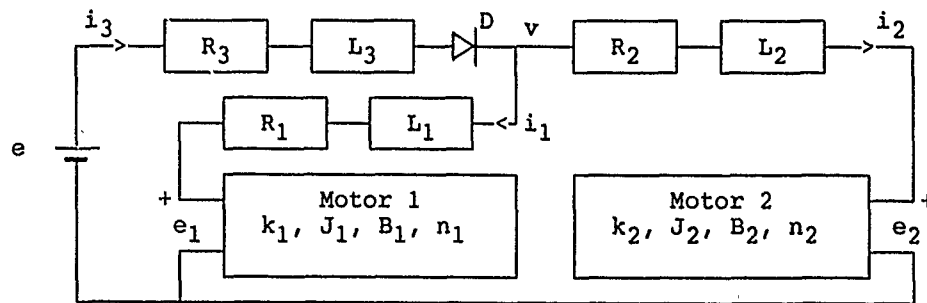


Fig 3. Twin Electric Motor Propeller Drive.

**Subsystem 1:** D is conducting; hence,  $i_3 = i_1 + i_2$ . If  $i_3 \leq 0$ , invoke subsystem 2.

$$\begin{bmatrix} L_1+L_3 & L_3 & 0 & 0 & 0 \\ L_3 & L_2+L_3 & 0 & 0 & 0 \\ 0 & 0 & J_1 & 0 & 0 \\ 0 & 0 & 0 & J_2 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} x + \begin{bmatrix} R_1+R_3 & R_3 & k_1 & 0 & -1 \\ R_3 & R_2+R_3 & 0 & k_2 & -1 \\ -k_1 & 0 & B_1 & 0 & 0 \\ 0 & -k_2 & 0 & B_2 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} x = \underline{0};$$

i.e.,  $L_1 x + R_1 x = \underline{0}$ .

$$y = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & R_2 & 0 & k_2 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & k_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & k_3 & 0 \end{bmatrix} x + \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & L_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} x;$$

i.e.,  $y = E_1 x + F_1 x$ .

$d = [1 \ 1 \ 0 \ 0 \ 0] x + \underline{0} x$ ; i.e.,  $d = G_1 x + H_1 x$ .

$M_1 = [1]$ ;  $s_1 = [2]$ .

**Subsystem 2:** D is not conducting; hence,  $i_3 = 0 = i_1 + i_2$ ; if  $(v - e \leq 0)$ , invoke subsystem 1. Here,  $i_1 = -i_2$ , they are therefore not distinct state components.

$$\begin{bmatrix} L_1+L_2 & 0 & 0 & 0 & 0 \\ 0 & L_1+L_2 & 0 & 0 & 0 \\ 0 & 0 & J_1 & 0 & 0 \\ 0 & 0 & 0 & J_2 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} x + \begin{bmatrix} R_1+R_2 & 0 & k_1 & -k_2 & 0 \\ 0 & R_1+R_2 & -k_1 & k_2 & 0 \\ -k_1 & 0 & B_1 & 0 & 0 \\ 0 & -k_2 & 0 & B_2 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} x = \underline{0};$$

i.e.,  $L_2 x + R_2 x = \underline{0}$ .

$$y = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 \\ 0 & R_2 & 0 & k_2 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & k_3 & 0 & 0 \\ 0 & 0 & 0 & k_3 & 0 \end{bmatrix} x + \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & L_2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} x;$$

i.e.,  $y = G_2 x + H_2 x$ .



$$d = [ 0 \ R_2 \ 0 \ k_2 \ -1 ] x + [ 0 \ L_2 \ 0 \ 0 \ 0 ] \dot{x}; \text{ i.e., } d = E_2 x + F_2 \dot{x}.$$

$$M_2 = [ 1 ]; \ s_2 = [ 1 ].$$

The following parameter values were inserted in the above equations:  $R_1 = 16.5 \ \mu\Omega$ ;  $L_1 = 0.26 \ \mu\text{H}$ ;  $R_2 = 89.2 \ \mu\Omega$ ;  $L_2 = 1.83 \ \mu\text{H}$ ;  $R_3 = 12.6 \ \mu\Omega$ ;  $L_3 = 0.20 \ \mu\text{H}$ ;  $k_1 = k_2 = 23.873 \ \text{NM/A}$ ;  $J_1 = J_2 = 30,000 \ \text{KgM}^2$ ;  $B_1 = B_2 = 0.0$ . The following initial conditions were employed:  $i_1(0) = i_2(0) = 30,0000 \ \text{A}$ ;  $n_1(0) = 180.87 \ \text{RPM}$  (18.94 Rad/s);  $n_2(0) = 180.00 \ \text{RPM}$  (18.85 Rad/s);  $e(0) = 100. \ \text{v}$ .

Figure 4 shows the computed transient response of the motors. Widely-different time scales in the left and right portions of the graphs show the contributions of electrical and mechanical time constants. The diode current  $i_3$  drops to zero in about 75 microseconds; the current and speed transients decay in about 150 milliseconds. Computation time for 98 output data vectors, including the subsystem transition at 74.5  $\mu\text{s}$ , was 3.5 seconds.

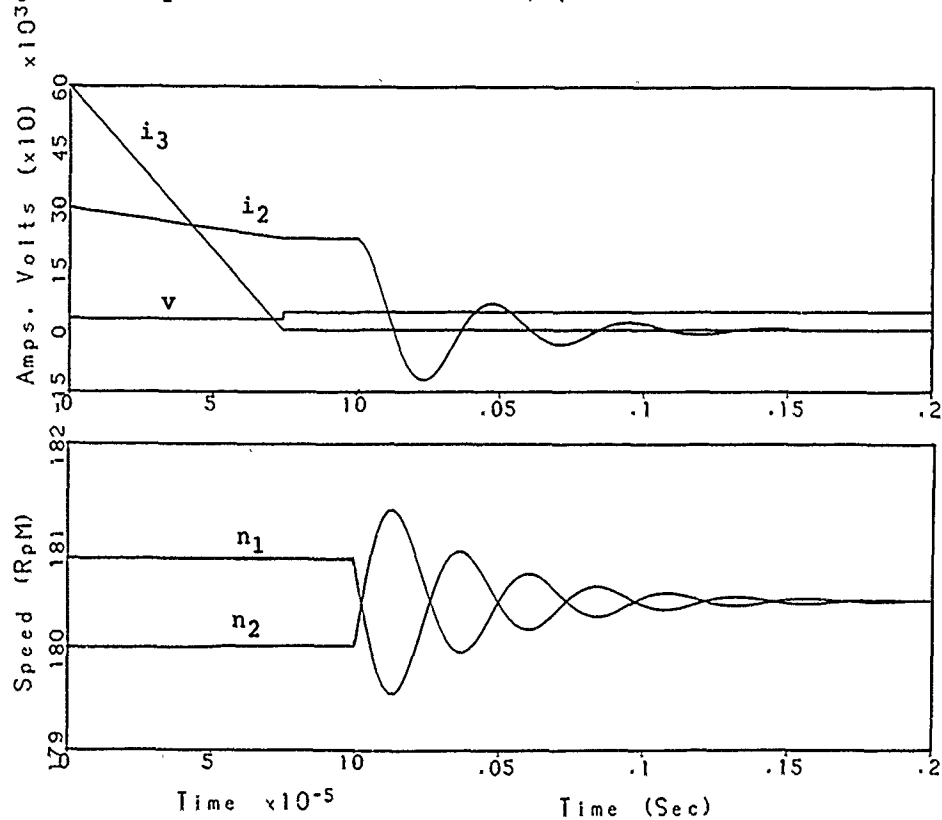


Fig 4. Electric Propeller Drive Transient Response.

**Example 2. Single-Phase Cycloconverter.** In the back-to back thyristor circuit of Fig 5, the positive and negative power-supply 'banks' consist of thyristors  $Q_1$  and  $Q_2$  respectively. The following (augmented) state assignment is made:

$$x = [i \ e_s \ e_c \ e_m \ e_n]^T.$$

$e_s$  and  $e_c$  are respectively the inphase and quadrature components of the supply-frequency sine wave;  $e_m$  and  $e_n$  are the corresponding components of the (low-frequency) modulating wave. Since  $e_c$  is already present, gate trigger waveforms are conveniently generated by the offset cosine method [9]. We record load current  $i$ , load voltage  $v$ , and modulating voltage  $e_m$ . Note that modulation index, defined as the ratio of the amplitude of  $e_m$  to that of  $e_s$ , may be readily set by choosing the initial values of  $x_2, x_3, x_4, x_5$ .

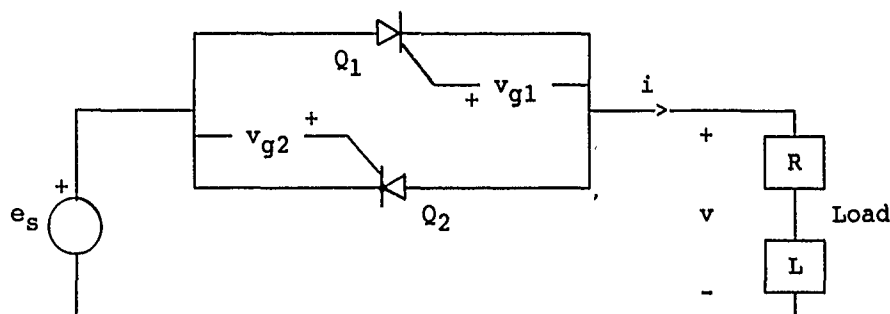


Fig 5. Single-Phase Cycloconverter Circuit.

**Subsystem 1:** Thyristor  $Q_1$  is conducting; therefore,  $v = e_s$ , and  $L di/dt + Ri - e_s = 0$ .

$$\text{State: } \begin{bmatrix} L & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} x + \begin{bmatrix} R & -1 & 0 & 0 & 0 \\ 0 & 0 & -w_c & 0 & 0 \\ 0 & w_c & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -w_m \\ 0 & 0 & 0 & w_m & 0 \end{bmatrix} x = \underline{0}.$$

$$\text{Output: } y = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix} x + \underline{0} x.$$

**Decision:** If  $i \leq 0$ , invoke subsystem 2.

$$d = [1 \ 0 \ 0 \ 0 \ 0] x + \underline{0} x; \quad M_1 = [1]; \quad s_1 = [2].$$

**Subsystem 2:** Thyristors  $Q_1$  and  $Q_2$  are NOT conducting; therefore  $i \equiv 0$ , and  $v = Ri + Ldi/dt \equiv 0$ .

$$\text{State: } \begin{bmatrix} L & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} x + \begin{bmatrix} R & 0 & 0 & 0 & 0 \\ 0 & 0 & -w_c & 0 & 0 \\ 0 & w_c & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -w_m \\ 0 & 0 & 0 & w_m & 0 \end{bmatrix} x = \underline{0}.$$

$$\text{Output: } y = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ R & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix} x + \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ L & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} x.$$

Decision: If  $e_s > 0$  AND trigger voltage  $v_1 = e_c - e_m > 0$  AND  $e_m > 0$ , invoke subsystem 1; if  $e_s < 0$  AND trigger voltage  $v_2 = e_m - e_c < 0$ , AND  $e_m < 0$ , invoke subsystem 3.

$$d = \begin{bmatrix} 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix} x + \underline{0} x; M_2 = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 \end{bmatrix};$$

$$s_2 = \begin{bmatrix} 1 \\ 3 \end{bmatrix}.$$

**Subsystem 3:** Thyristor  $Q_2$  is conducting; therefore,  $v = e_s$  and  $Ldi/dt + Ri - e_s = 0$ .

$$\text{State: } \begin{bmatrix} L & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} x + \begin{bmatrix} R & -1 & 0 & 0 & 0 \\ 0 & 0 & -w_c & 0 & 0 \\ 0 & w_c & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -w_m \\ 0 & 0 & 0 & w_m & 0 \end{bmatrix} x = \underline{0}.$$

$$\text{Output: } y = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix} x + \underline{0} x.$$

Decision: If  $i \geq 0$ , invoke subsystem 2.

$$d = \begin{bmatrix} -1 & 0 & 0 & 0 & 0 \end{bmatrix} x + \underline{0} x; M_3 = \begin{bmatrix} 1 \end{bmatrix}; s_3 = \begin{bmatrix} 2 \end{bmatrix}.$$

The curves of Fig 6 were plotted for the following parameter values:  $L = 2.0$  mH,  $R = 2.0$   $\Omega$ ;  $w_c = 377$  rad/s,  $w_m = 42$  rad/s; peak values of  $e_s$  and  $e_m$  are 100. v and 90. v respectively. Time-step size is  $5.0 \times 10^{-4}$  (0.5 ms). The time required to compute and file

333 data points, of which 32 transition times were found by interpolation, was 18.4 seconds.  $x(0) = [0.0. -100.0. 90.]^T$ , in subsystem 2. The discontinuous nature of the load current in this example recommends the use of multi-phase ac power sources and/or larger smoothing inductance.

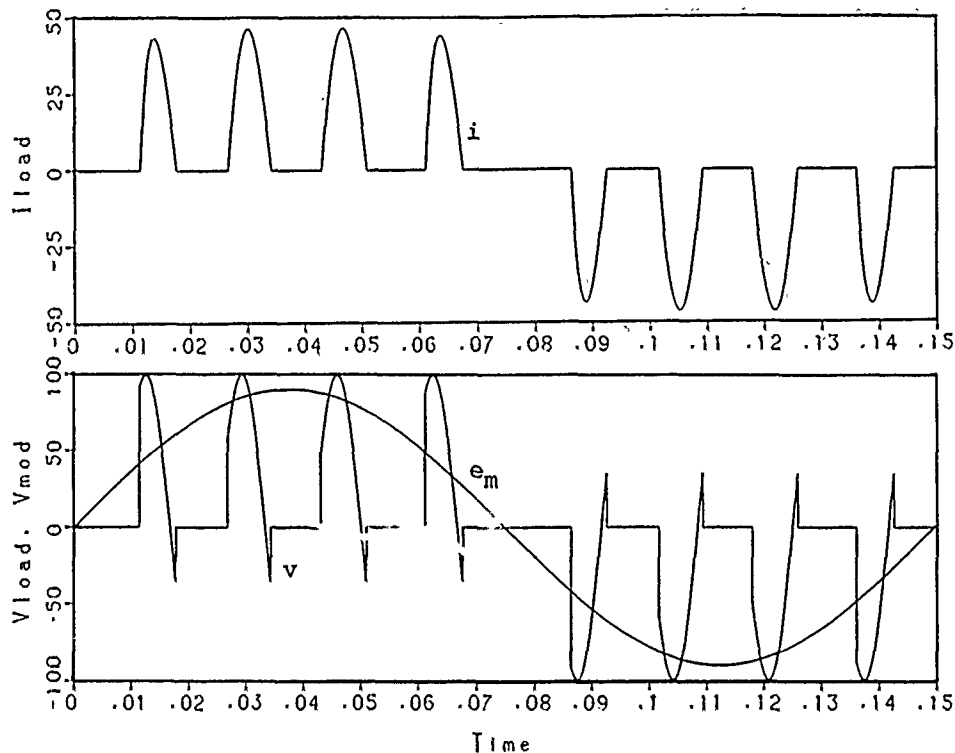


Fig 6. Cycloconverter Response.

## 5 CONCLUSION

We have summarized supporting theory appropriate to the systematic modelling of piecewise linear (time-invariant) systems using state-space methods. The universality of the method resides in the employment of state-dependent decision vectors and logic-based 'mask' matrixes to cope with the variable-structure nature of such systems.

We have described a programme for computing the dynamic response of piecewise linear system models which retains the accuracy and most of the speed inherent in linear state-space methods. While feasibility of the method has been demonstrated, more-flexi-

ble data entry routines and more efficient programming would enhance its convenience and speed.

We have demonstrated the simulation method with the aid of unadorned examples from the area of electronically-controlled electric drives. More complete models could be analyzed using the techniques developed above, provided only that the additional components be described by linear ordinary differential equations with constant coefficients.

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